A STUDY IN CHARCOAL

by

W. S. H. Cleghorne

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A STUDY IN CHARCOAL.

Being a research on charcoals made from exotic woods grown in the Union of South Africa.

by

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The various samples of charcoal were supplied by the Forest Department in five-bag lots, together with the following details with regard to their manufacture, etc:

Eucalyptus resinifera :

This charcoal was burned by the "Fort Cunynghame method" described on Pages 6 to 8 of Bulletin No. 1 of 1919, compiled by Mr. J.J. Kotze, B.A., B.Sc., Acting Forest Research Officer of the Forest Department, Union of South Africa. Also pages 9, 11 and 12 of the same Bulletin, revised in March, 1920. Further particulars are:

Age of wood	8 years
Size	2" to 6" diameter
Degree of dryness	green

Carbonized with bark on

Manufactured at Jessievale, P.O. Vosmansbeacon, via Carolina, Ermelo District, November, 1919.

Eucalyptus viminalis :

Method of burning	In cast iron retort
Age of wood	9 years
Size	3" to 5" in diameter
Degree of dryness	Half-dry

Carbonized with bark on

Manufactured at Pan Plantation, Middelburg, Transvaal, January, 1920.

Eucalyptus saligna :

Method of burning	Fort Cunynghame
Age of wood	6 years
Size	3" to 5" diameter
Degree of dryness	Very dry.

Carbonized with bark on.

Manufactured at Jessievale, Spetember, 1919.

Eucalyptus sideroxylon :

Method of burning	In cast iron retort.
Age of wood	11 Years.
Size	4" to 5" diameter.
Degree of dryness	Half dry.

Carbonized with bark on.

Manufactured at Pan, Middelburg, Transvaal, August, 1919.

Eucalyptus tereticornis :

Method of burning	In cast iron retort.
Age of wood	12 Years.
Size	3" to 5" diameter.
Degree of dryness	Half dry.

Carbonized with bark on.

Manufactured at Pan, September, 1919.

Eucalyptus maidenii :

Method of burning	In cast iron retort.
Age of wood	9 Years.
Size	3" to 5" diameter.
Degree of dryness	Half dry.

Carbonized with bark on.

Manufactured at Pan, January, 1920.

Pinus insignis (Pan) :

Method of burning	In cast iron retort.
Age of wood	9 Years.
Size	3" to 5" diameter.
Degree of dryness	Half dry.

Carbonized with bark on.

Manufactured at Pan, January, 1920.

<u>Pinus insignis</u> (Fort Cunynghame) :

<u>Pinus pinaster</u> (Fort Cunynghame) :

Method of burning: The method of manufacture was as given in Schlich's Manual of Forestry, Vol. V., pages 708-9 (pages 540-2, second edition) the wood being cut to 4-foot billets. Owing to a sudden gale on a Sunday, although the kilns were protected by a wattle screen, both kilns fired badly, and it was with some difficulty that any portion was saved.

Age of wood	29 Years.
Size	3" to 5" diameter.
Degree of dryness	Quite dry.

Carbonized with bark on.

Manufactured at Fort Cunynghame Plantation (Toise River Station), November, 1919.

<u>Pinus taeda</u> :

Method of burning	"Fort Cunynghame Method".
Age of wood	9 Years.
Size	2" to 4" diameter.
Degree of cryness	Very dry.

Carbonized with bark on.

Manufactured at Jessievale, December, 1919.

<u>Cupresses lusitanica</u> :

Method of burning	"Fort Cunynghame Method".
Age of wood	7 Years.
Size	2" to 4" diameter.
Degree of dryness	Very dry (and sound).

Carbonized with bark on.

Manufactured at Jessievale, November, 1919.

Acacia decurrens, var. mollis :

(Black Wattle).

Method of burning	"Fort Cunynghame".
Age of wood	7 Years.
Size	2" to 4" diameter, poles 20 to 25 ft. long.
Degree of dryness	Very dry.

Carbonized with bark off.

The wood before conversion into charcoal lay in the plantation fully exposed to all weather conditions.

Manufactured at Jessievale, August, 1919.

Acacia cyclopis :

Acacia saligna :

Method of burning : The pieces were stacked in a conical form measuring 15 feet diameter at the base and 7½ feet high. The stack or kiln was then covered with green cyclopis branches free from seed pods. This thatch of green branches was then entirely covered with sand three inches thick. The fire was started at the top of the kiln and drawn towards the base by means of vent spaces. When the kiln was finished it was covered with another layer of sand beaten down firmly and left for two days to cool.

Age of wood	Freshly cut.
Size	½" to 3½" diameter x 2½ feet long.

Manufactured at Eerste River Forest Reserve, Cape Peninsula.

OBJECTS AND METHODS OF THE TESTS.

The object of the research was to endeavour to classify the different charcoals by the following methods :

1. Proximate analysis of the charcoal,

2. Measurement of the fuel consumption per brake horse-power......

horse-power hour on suction gas engine trial at constant given load, for 6 hours' run.

3. Analysis of the gas from the gas producer while the engine was on the trial mentioned under 2.

4. Measurement of the weight of each charcoal per given volume.

5. The discovery of any consistent relationships between the various quantities measured.

Beyond these initial objects, others which became apparent as the work progressed were pursued.

ENGINE TRIALS.

The engine used was a "P" type "National" suction gas engine drawing gas from a "B"-size "National" producer. Every precaution was taken to have conditions as uniform as possible over all the trials. For the purposes of these trials, a flexible water-seal joint was inserted in the pipe conveying the gas from the producer to the scrubber, and the former was placed on the platform of a weighing machine so that the fuel consumption could be determined with the maximum degree of accuracy. The need of great accuracy in measuring the fuel consumption will be clear when it is stated that in some cases the total fuel consumption was less than sixty pounds. Further, the engine was run for at least one hour on the test load before the commencement of the six hours' trial, and stoking was arranged to occur a quarter of an hour before the commencement, and the same time before the end, of the trial, so that condition in the producer might be as nearly as possible the same at the beginning and end of the trial.

The engine, when new, was capable of delivering 11 B.H.P. at the altitude of Potchefstroom, viz: 4,430 feet above sea level, but, being somewhat worn by the date of the trials, the maximum l that it was considered safe to expect the engine to maintain on trial was about 7½ B.H.P., and at approximately that load each

trial was ....

trial was run. A water-cooled Prony brake was used, and indicator diagrams were taken at regular intervals during each trial in order to keep in touch with the working of the engine. The cams on the half-time shaft were considerably worn. In the accompanying indicator diagrams this is most clearly shown by the indication of late opening of the exhaust valve.

TEST OF THE PRODUCER GASES.

The gas samples were taken after the gas had passed through the scrubber, so the gas analysed was such as was actually supplied to the engine. In this connection, however, it should be borne in mind that some of the carbon dioxide and hydrocarbons in the gases as they leave the producer would be likely to be absorbed by the water in the scrubber.

For the gas analyses an Orsat-Lunge gas analysis apparatus, fitted with a palladium-asbestos tube was used.

In all but one case - that of Eucalyptus viminalis, in which the gas sample was drawn over a long period - two samples of gas were taken and analysed for each charcoal tested. In the case of duplicate engine trials this was done for some of the Eucalypts (which were tested early in the course of the research) in only one of the duplicate trials. Later on, however, when found to be advisable, it was done in all cases, the first gas sample being taken during the first hour of the engine trial and the second sample during the fifth hour. Each sample of the gas was drawn over a period of about 25 minutes. The gas samples were collected over mercury. Every precaution was taken to secure accurate results in the gas analyses, to each of which from 2½ to 3 hours were devoted. Thus, after the carbon monoxide had been absorbed in the carbon-monoxide absorption pipette, which contained acid solution of cuprous chloride, the residual gases were taken back into the carbon-dioxide absorption pipette in order to find if any acid fumes were present. Further, the palladium-asbestos tube and adjoining parts were allowed to cool off completely,

before ....

before measuring the contraction of the gases after they had been passed through the tube.

While the author was awaiting the arrival of apparatus from abroad, he made proximate analyses of the samples of charcoal as they arrived.

An air-dried sample of each charcoal was prepared by finely powdering it, heating it for an hour to a temperature of 55 degrees Centigrade, and then spreading it out exposed to the atmosphere of the room, but protected from dust, for two days.

The following results were obtained :

Table No. 1.

PROXIMATE ANALYSES OF CHARCOALS WHEN RECEIVED

	Per-cent Moisture	Per-cent Volatile Matter	Per-cent Fixed Carbon	Per-cent Ash.
Eucalyptus resinifera	7.94	14.40	76.47	1.19
Eucalyptus viminalis	5.85	18.91	72.87	2.37
Eucalyptus saligna	2.89	5.60	90.59	0.92
Eucalyptus sideroxylon	3.74	19.29	75.37	1.60
Eucalyptus tereticornis	3.71	21.35	73.82	1.12
Eucalyptus maidenii	8.27	8.50	80.71	2.52
Pinus insignis (Pan)	6.81	17.45	74.29	1.45
Pinus insignis (Fort Cunynghame)	6.58	15.76	76.47	1.19
Pinus pinaster	9.04	11.79	78.25	0.92
Pinus taeda	7.81	10.71	80.14	1.34
Cupressus lusitanica	4.51	10.20	83.84	1.45
Acacia decurrens var. mollis (Black Wattle)	1.86	9.42	88.08	0.64
Acacia cyclopsis	3.44	31.10	62.82	2.64
Acacia saligna	5.00	8.80	83.77	2.43

The method employed in making the above proximate analyses,

as well as ....

as well as those of the charcoals as fed to the producer during the engine trials, was as follows :

Moisture Test.

One or two grams of the test sample were placed in a glass weighing bottle, weighed on a chemical balance, heated in a dry-air oven to 105 degrees Centigrade for half-an-hour, stoppered and placed in a desiccator till cool, then weighed again. This was repeated, the sample being heated for half-an-hour each time till its weight began to increase. The minimum weight recorded was used in determining the moisture contents. To be quite accurate, column 1 of the preceding Table, and column 8 of Table No. 2, should be headed : "Per cent moisture plus occluded gases driven off at 105 degrees Centigrade".

Test for Volatile Matter.

One or two grams of the sample was placed in a platinum crucible with lid, weighing about 16½ grams. The crucible was heated by means of a Bunsen flame, and allowed to cool, alternately, each time a higher temperature being reached before particles of charcoal began to be driven off. Then the crucible was heated over the full flame of a Bunsen burner for six minutes. The crucible was supported on a triangle of platinum wire with its bottom 6 to 8 centimetres above the top of the burner, the flame being 20 cms. high when the crucible was removed. The tests were made in a place free from draughts. The procedure recommended by the "Committee on Coal Analysis", Journal of the American Chemical Society, 1899, Vol. XXl, was followed as closely as possible with the above-mentioned modification i.e. alternate heating and cooling with gradually increasing temperature till the sample could stand the desired temperature without particles being driven off. The loss of weight represented the amount of volatile matter and moisture in the sample. Subtracting the known weight of moisture gave the weight of volatile matter.

Ash Test.

The sample was intensely heated in the open crucible until all the carbon was burned away.

Fixed Carbon.

The percentage of fixed carbon is the difference between 100 and the sum of the percentage weights of moisture, volatile matter and ash.

Analyses of Charcoals as fed to Producer.

The percentages of moisture plus occluded gases driven off at 105 degrees Centigrade, and of volatile matter, in the charcoals as fed to the producer during the engine trials, are given in columns 8 and 9, Table No. 2. For these analyses representative samples were taken, as the charcoal was being fed to the producer, quickly ground in a mortar, and kept in sealed bottles till analysed. Between these analyses and the first-made proximate analyses, the five-bag samples of charcoal were stored in a dry shed for nine months or, in some cases, longer, depending on the order of the reception of the samples and the testing thereof.

Thus, before the second analyses and the engine trials the charcoals had time to reach conditions that were probably steady. This view is borne out by the comparatively small differences (in column 8, Table No. 2) in the percentages of moisture plus occluded gases in the different species of each genus. Further, as shown by these percentages the Pines sort themselves out from the Eucalupts and Acacias, the average percentage moisture plus occluded gases for the three genera being as follows:

Table No. 3.

	Average percentage of moisture, plus occluded gases driven off at 105 degrees Centigrade.
Eucalypts	5.30
Acacias	5.82
Pines	7.41

This figure in the case of the pines is higher than for the other genera; doubtless on account of the greater volume, per unit weight, of the pines.

A representative sample of the Natal Anthracite as fed to the producer during the engine trial was also analysed with the result, also given in columns 8 and 9, Table No. 2 :

Table No. 4.

Per-cent moisture plus occluded gases driven off at 105 degrees Centigrade	Per-cent Volatile Matter	Per-cent Fixed Carbon	Per-cent Ash
4.59	6.15	73.20	16.06

The high percentage of ash is characteristic of South African coals.

Probable Accuracy of the Engine Trials and Gas Analyses.

In the case of seven different fuels it was possible to run engine trials in duplicate. The following table of results, and calculated per-cent difference between the fuel consumption in any two engine trials with the same fuel, shows that in no such case is the difference more than 3.2 per cent.

Table No. 5.

TABLE SHOWING ACCURACY OF DUPLICATE ENGINE TRIALS.

Kind of fuel		Fuel consumption per brake horse-power hour in lbs	Per-cent difference in fuel consumption	Lower calorific value of gas in British thermal units per cubic foot
Eucalyptus viminalis	1st.trial	1.39	2.9	140.5
" "	2nd.trial	1.35 l		151.9 h
Eucalyptus saligna	1st.trial	1.52	0.65	133.1
" "	2nd. "	1.53		135.5
Eucalyptus tereticornis	1st.trial	1.45	2.0	-
" "	2nd. "	1.48		150.5
Pinus insignis (Fort C.)	1st.trial	1.48	2.6	133.8
" " "	2nd. "	1.52 h		131.6 l
Pinus pinaster	1st.trial	2.17	3.2	127.0
" "	2nd. "	2.10 l		137.0 h
Black Wattle	1st.trial	1.55	1.3	137.1
" "	2nd. "	1.57 h		131.9 l
Natal anthracite	1st.trial	1.71	1.7	114.5
" "	2nd "	1.68 l		124.7 h

That conditions were kept very constant over a number of engine trials is evidenced from the fact, to take only one instance, that duplicate tests of Eucalyptus viminalis charcoal were made on 15th. October, 1920, and 10th. November, 1920, respectively, three engine trials with other charcoals as fuel having been run between these dates. Yet the difference in the fuel consumption of Eucalyptus viminalis charcoal between that on 15th. October and that on 10th. November was only 2.9 per cent.

As a further.........

As a further indication of the accuracy of both the engine trials and the gas analyses, it will be noticed from the above table (No. 5) that when in any one pair of duplicate trials the fuel consumption is lower for the second trial than for the first, then the calorific value of the gas is higher for the second than for the first, and _vice versa_. This has been indicated by the insertion of the letters h (high) and l (low) in the table.

In the case of _Eucalyptus saligna_, the fuel consumption in each one of the duplicate trials are substantially equal, as are also the calorific values of the gas.

Differences in the quantity of gas produced per pound of fuel consumed may, of course, have affected the results, but such differences could only be slight - because the trials were run as similarly as possible. Evidently this has been the case, as such differences have not been of sufficient magnitude to obscure the above-mentioned rational relationship of high calorific value of the gas corresponding with low fuel consumption. It should here be mentioned that in each case the calorific value of the gas was calculated from the figures of the gas analysis, the "lower" calorific value being taken.

Effect of Duration of Run on Composition of Gas.

As already mentioned, two samples of gas were drawn for analysis, the first during the first hour of the trial-run and the second during the fifth hour. Reference to column 4, Table No. 2, shows that, in general, the later sample contained more carbonic acid gas, less carbon monoxide, more hydrogen, more methane and less nitrogen than the earlier sample.

Take, for example, the figures for _Pinus pinaster_, 18th. May, 1921, comparing the analysis of the second sample of gas with that of the first, notwithstanding the great increase in carbonic acid gas, from 6.1 to 9.9 per cent, the hydrogen gas has increased from 11.6 to 19.8 per cent, while the carbon monoxide has decreased from 22.4 to 16.9 per cent. These changes are explained by the

circumstance.......

circumstance that carbon monoxide at a high temperature decomposes steam so that part of that gas, which would otherwise have appeared in the mixture, has disappeared forming carbonic acid gas and hydrogen according to the following equation :

$$CO + H_2O = CO_2 + H_2$$

Since the temperature of the producer in the fifth hour of the engine trial was higher than in the first, one would expect the second sample of producer gas to contain more carbonic acid gas, more hydrogen and less carbon monoxide than the sample taken during the first hour. This expectation is justified by the results of the author's analyses in practically every case.

No doubt, also, the increase in methane in the second gas sample over that in the first can be ascribed to the higher temperature of the producer towards the end of the trial, which increases the velocity of the reactions forming methane.

It happened, quite fortuitously, in the case of two duplicate engine trials, that one trial was run in cool weather and the other (check) trial in hot weather, the charcoals consumed being Eucalyptus resinifera and Eucalyptus sideroxylon respectively. Tabulating the production of methane and the mean engine-room temperature during the trial we have :

Table No.6.

Charcoal used in engine-trial	Percentage of Methane in producer gas	Mean temperature of engine-room
Eucalyptus resinifera " "	0.7 (First hour) 0.6 (Fifth hour)	73 degrees Fah.
Eucalyptus resinifera " "	2.9 (First hour) 3.6 (Fifth hour)	89 degrees
Eucalyptus sideroxylon " "	1.2	76 degrees
Eucalyptus sideroxylon " "	2.9 (First hour) 3.4 (Fifth hour)	89.5 degrees

The above ....

The above results seem to indicate that at higher engine-room temperatures more methane is produced than at lower engine-room temperatures. Since the tests were not arranged with reference to this point, more definite indications cannot be given. To settle the matter, it would be necessary to run a series of trials in the winter and an exactly similar series, with the same samples of charcoal, in the summer-time.

Relationship between the Quantity of Volatile Matter in the Charcoal and the Calorific Value of the Gas.

The following table appears to indicate that when the per-cent weight of volatile matter in a charcoal is high the calorific value of the producer gas per cubic foot at normal temperature and pressure is also high and *vice versa*.

Table No. 7.

EUCALYPTS.

Kind of charcoal	Per-cent weight of volatile matter in the charcoal	Lower calorific value of producer gas in British thermal units per cubic foot
Eucalyptus saligna	7.92	135.5
Eucalyptus maidenii	9.49	136.5
Eucalyptus resinifera	9.53	140.8
Eucalyptus viminalis	17.05	146.2
Eucalyptus tereticornis	17.48	150.5
Eucalyptus sideroxylon	21.98	144.7

In the above table, with the exception of *Eucalyptus viminalis*, only the results of these trials are taken in which the gas samples were drawn during the 1st. and 5th. hour respectively. The values for *Eucalyptus viminalis* were accepted, because the gas samples were drawn over a long period, extending over nearly the whole of the trial.

Table No. 8. ....

Table No. 8.

PINES.		
Kind of charcoal	Per-cent weight of volatile matter in the charcoal	Lower calorific value of producer gas in British thermal units per cubic foot.
Pinus insignis (Fort Cunynghame)	11.06	132.7
Pinus pinaster	13.14	132.0
Pinus taeda	17.03	142.5
Pinus insignis (Pan)	17.53	143.4

Table No. 9.

ACACIAS.		
Kind of charcoal	Per-cent weight of volatile matter in the charcoal	Lower calorific value of producer gas in British thermal units per cubic foot.
Acacia decurrens var mollis (Black Wattle)	9.87	134.5
Acacia saligna	14.68	146.9
Acacia cyclopis	31.61	149.8

The above relationship is shown graphically by the "curves" given in Fig.1. It will be noticed that the Pines again clearly separate themselves from the Eucalypts and Acacias. The three curves are remarkably similar, showing approximately the same rate of increase of calorific value of the producer gas with increasing percentage weight of volatile matter in the charcoal.

Eucalyptus sideroxylon shows a lower calorific value of the gas than might be expected, no doubt due to the very thick bark of this tree (really the point representing *Eucalyptus sideroxylon* lies on quite another curve, viz: that of the "ironbarks") but the curve of the Acacias almost strikes an average between the points

on the ....

Eucalypt-curve, the rate of increase in the calorific value of the gas being high up to a certain point - represented by <u>Acacia saligna</u> in the Acacia curve - and then lower after that point has been passed.

<u>Rich Gas shown by the Indicator Diagrams.</u>

The difference between a rich producer gas, i.e. one of high calorific value, and a poor one was clearly shown by the indicator diagrams and also by the number of explosions. In order to illustrate this, average indicator cards for <u>Acacia cyclopis</u> charcoal and anthracite (which gave the poorest gas of all) are reproduced in Figs 2 and 3 respectively. The indicator piston in the case of the <u>Acacia cyclopis</u> charcoal was driven hard against the "stop", the spring not being strong enough for this gas. The strongest spring available, $\frac{1}{100}$, was used in each case. The higher expansion line (with "weak-spring" oscillations) is noticeable in the case of the <u>Acacia cyclopis</u> charcoal. The total number of explosions during the six hours' test were :

<u>Acacia cyclopis</u>	36,253
Anthracite	40,700

<u>Volume of Gas Produced per Pound of Charcoal.</u>

Chiefly on account of the expense involved, direct measurement of this could not be carried out, but relative quantities were calculated as follows :

$$\left.\begin{array}{l}\text{B.Th.U's per}\\ \text{B.H.P. hour}\\ \text{sent to engine}\end{array}\right) = \left(\begin{array}{l}\text{Fuel consump-}\\ \text{tion per B.H.P}\\ \text{hour in pounds}\end{array}\right) \times \left(\begin{array}{l}\text{Quantity of}\\ \text{gas per 1 lb.}\\ \text{of fuel, in c.ft.}\end{array}\right) \times \left(\begin{array}{l}\text{Calorific}\\ \text{value of the}\\ \text{gas per c.ft.}\end{array}\right.$$

therefore :

$$\left.\begin{array}{l}\text{Quantity of gas per 1 lb. of fuel}\\ \text{in cubic feet}\end{array}\right) = \frac{\text{B.Th.U's per B.H.P. hour sent to engine}}{\left(\begin{array}{c}\text{Fuel consumption}\\ \text{per B.H.P. hour in}\\ \text{pounds}\end{array}\right) \times \left(\begin{array}{c}\text{Calorific value of}\\ \text{the gas, per cubic}\\ \text{foot.}\end{array}\right)}$$

But the numerator on the right-hand side of this equation is constant since the engine ran on the same load and, as far as possible, under the same conditions in each trial, hence :

Quantity of ....

$$\text{Quantity of gas per 1 lb. of fuel, in cubic feet} = \frac{K}{\left(\begin{array}{l}\text{Fuel consumption}\\ \text{per B.H.P. hour}\\ \text{in pounds}\end{array}\right) \times \left(\begin{array}{l}\text{Calorific value of}\\ \text{the gas, per cubic}\\ \text{foot.}\end{array}\right)}$$

In order to obtain suitable relative figures the constant K was taken equal to 1,000 and the relative quantities of gas per one pound of fuel calculated with the following results:

Table No 10.

Charcoal	Quantity of gas per 1 lb. of charcoal proportional to :	Lower calorific value of the gas, B.Th.U's per cubic foot.
Eucalyptus resinifera	5.15	140.8
Eucalyptus viminalis	5.00	146.2
Eucalyptus saligna	4.88	135.5
Eucalyptus sideroxylon	5.08	144.7
Eucalyptus tereticornis	4.53	150.5
Eucalyptus maidenii	5.02	136.5
Pinus insignis (Pan)	4.08	143.4
Pinus insignis (Fort Cunynghame)	5.02	132.7
Pinus pinaster	3.55	132.0
Pinus taeda	4.23	142.5
Cupressus lusitanica	4.68	141.5
Acacia decurrens, var. mollis (Black Wattle)	4.77	134.5
Acacia cyclopis	3.79	149.8
Acacia saligna	5.27	146.9
Natal anthracite	4.93	119.6

The figures in the above table have been plotted, giving the curves of Fig 4.

Here, again, the Acacia curve follows that of the Eucalypts very closely........

very closely, while the Pine curve, of course, is separated on account of the lower calorific values of the pines as a whole.

The similarity of all three curves is noteworthy, all being concave towards the left, showing that at low calorific values of the gas the volume of gas produced per pound of charcoal increases as the richness of the gas increases, but that at higher calorific values of the gas the volume of gas per pound of charcoal decreases as the richness of the gas continues to increase.

The best charcoals from this point of view, are of course those that are furthest away from the origin of co-ordinates.

Relative Volumes of the Charcoals per Unit Weight.

In order to arrive, in a practical way, at the relative volumes of the charcoals, representative samples were roughly ground in a mortar and passed through a sieve with one-third inch meshes. The charcoal that passed this sieve then had the dust screened out through a sieve with one-sixteenth inch meshes, and was weighed. A tin mug 4 inches diameter by 3¾ inches deep, inside, (capacity 47 cubic inches) was filled with the sample of charcoal to be weighed, the latter being gently shaken down and struck off level with the top edge of the mug. Each charcoal was in practically the same condition as to moisture etc., as when fed to the producer during the engine trials. The mug was filled three times with a different portion of the sample, and three weighings made for each charcoal. The Natal anthracite was put through the same test.

Note that the only wood that was carbonized with the bark off was Acacia decurrens, var. mollis. This would be done in practice, the bark being used for the manufacture of wattle-bark extract for tanning purposes.

The following results were obtained :

Table No. 11. ......

Table No. 11.

Kind of charcoal	1st. Weighing	2nd. Weighing	3rd. Weighing	Mean of three Weighings.
Eucalyptus resinifera	212.7	214.7	211.6	213.0 grams
Eucalyptus viminalis	205.7	202.6	206.2	204.8
Eucalyptus saligna	185.0	187.3	190.0	187.4
Eucalyptus sideroxylon	212.6	205.0	218.4	212.0
Eucalyptus tereticornis	222.1	228.6	225.3	225.3
Eucalyptus maidenii	215.0	218.7	216.6	216.8
Pinus insignis (Pan)	124.3	129.9	134.9	129.7
Pinus insignis (Fort Cunynghame)	131.4	136.2	141.0	136.2
Pinus pinaster	167.7	176.0	177.5	173.7
Pinus taeda	127.4	118.2	119.1	121.6
Cupressus lusitanica	102.6	101.9	104.7	103.1
Acacia decurrens, var. mollis (Black Wattle)	194.2	200.1	199.9	198.1
Acacia cyclopis	272.7	271.0	271.9	271.9
Acacia saligna	249.8	238.8	246.3	245.0
Natal anthracite	674.7	665.7	682.1	674.2

Having figures of the weight of each fuel per given volume and also the fuel consumption per B.H.P. hour in pounds, figures proportional to the volume of fuel consumed per B.H.P. hour can be calculated. This has been done, and the results tabulated in column 11, Table No. 2. These figures were then plotted against the corresponding fuel consumption in pounds per B.H.P. hour, giving the graphs shown in Fig. 5.

Once more part of the Acacia curve practically strikes an

average ....

average through the points of the Eucalypt curve. Due mostly to the lesser weight per unit volume of the Pines, the curve of these charcoals is well separated from the Eucalypt and Acacia curves.

The curves given in Fig. 6, namely : quantities proportional to volume of producer gas (per pound of charcoal) multiplied by the calorific value of the gas per cubic foot plotted against weight of samples of ground charcoal per 47 cubic inches, again show a resemblance between the curves of the different genera.

In each genus volume of gas multiplied by its calorific value per cubic foot increases at first with increase in the "density" of the charcoal, and then falls off again after reaching a maximum.

Plotting the volume of gas produced per pound of charcoal against weight of ground charcoal per 47 cubic inches gave very similar curves to those in Fig. 6, showing that this volume is the preponderating factor.

The two preceding paragraphs may be summed up by saying that, in each genus, charcoals of medium weight per unit volume produce the greatest volume of gas per pound of charcoal, and also give the highest values of :- volume of gas per pound of charcoal multiplied by the calorific value of the gas per cubic foot.

From the information in the preceding part of this thesis the following has been extracted :

The charcoals which gave the richest producer gas in each genus are :

1. Eucalyptus tereticornis. Acacia cyclopis. Pinus insignis (Pan).

The charcoals of which the least weight was consumed per brake horse-power hour are :

2. Eucalyptus sideroxylon, Eucalyptus viminalis, Eucalyptus resinifera } nearly equal. Acacia saligna. Pinus insignus (Fort C

The charcoals ......

The charcoals that gave the greatest volume of gas per pound of charcoal (calculated from 1 and 2) in each genus are :

3. Eucalyptus resinifera Acacia saligna Pinus insignis (Fort C.)

The charcoals of which the least volume was consumed per brake horse-power hour are :

4. Eucalyptus resinifera, Eucalyptus sideroxylon, Eucalyptus tereticornis, Eucalyptus viminalis, Eucalyptus maidenii (nearly equal) Acacia saligna Pinus insignis (Fort C

The charcoals that gave the highest value : proportional volume of gas produced (per pound of charcoal) multiplied by its calorific value per cubic foot are :

5. Eucalyptus sideroxylon, Eucalyptus viminalis, Eucalyptus resinifera (nearly equal) Acacia saligna Pinus insignis (Fort C)

It is of importance to note that Acacia saligna, from which such excellent results were obtained, is the common Port Jackson Wattle of the Cape Flats. It is quick growing, but tender to severe frosts, and yields useful tan bark.

6. The relative mean weights per unit volume (measured as stated) taking that of the Pines as unity, are :

Pines		Eucalypts		Acacias		Natal anthracite
1	:	1.5	:	1.7	:	4.8

Cupressus lusitanica gave the lightest charcoal: about three-quarters as heavy as the average of the pine charcoals.

Reference to earlier Work on this Subject.

The only previous investigational work that, to the knowledge of the present writer, has been done in South Africa on this subject, is to be found mentioned in the "Agricultural Journal of the Cape of Good Hope", Volume XXXlll, pages 710-712,

where ....

where proximate analyses of charcoals made from Willow, Kaffir Thorn and Karree are given. Further, a few notes are presented on the relative consumption, by a suction gas plant, of these three charcoals but no accurate measurements of consumption per brake horse-power hour appear to have been made. The data in question were given by Mr. F.B. Parkinson, Assoc. R.S.M., F.R.G.S.

For descriptions of the various kinds of kilns and methods of burning, with the yields of charcoal therefrom, the reader is referred to the bulletin of the Forest Department of the Union of South Africa : "Wood Charcoal and its Manufacture", by J.J. Kotzé, B.A., B.Sc., Acting Research Officer.

POTCHEFSTROOM, TRANSVAAL.

7th. October, 1921.

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Institution of Electrical Engineers.

GLASGOW LOCAL SECTION.

SOME PHENOMENA OF COMMUTATION.

BY
Professor F. G. BAILY, M.A., F.R.S.E.,
and
Mr. W. S. H. CLEGHORNE, B.Sc., Carnegie Research Student.

(*Paper read November* 13, 1906.)

Reprint from the Journal of Proceedings of the Institution of Electrical Engineers, 1907, Part 181, Vol. 38.

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(*Paper read November* 13, 1906.)

In this paper will be described some experiments on the phenomena occurring in the process of the commutation of armature currents in direct-current dynamos and motors. It is a subject upon which much has been written, and already much experimental work has been carried out. With the theoretical writings the authors do not propose to deal, beyond an occasional reference where the experimental results corroborate or correct the assumptions of the writers. Some of the experimental work to be described is substantially a repetition of earlier work, but amplified to more exact determinations, or carried out in a different manner. The authors trust to be excused if they fail to make appropriate reference to the many papers which have been published in many languages.

The paper deals with the contact resistance of the brush, the value of the brush current, the currents in the short-circuited coils, and the electromotive force between the segment and the trailing edge of the brush.

In equations connecting the currents and E.M.F.'s under the brushes in direct-current machines it is frequently assumed that the resistance of the brush contact and brush is a constant, although it has been shown by Mr. A. H. Moore, Dr. E. Arnold, Mr. E. B. Raymond, and probably others, that this is by no means the case. Current density, speed, and pressure all exert an influence on the resistance, and the experiments to be described are a more exhaustive repetition of the work above mentioned. There were some discrepancies to be noticed in their results, and the precise effects of speed and pressure had not been examined closely, so that a full investigation appeared desirable. The influence of the character of the brush holder and the effect of lubricants were also points to be elucidated.

The mode of experiment was of the simplest character. A cast-iron pulley was covered with a heavy band of copper, turned and polished to a true surface with a diameter of 11 ins. This was mounted on the spindle of an electric motor. The two carbon brushes were set on the horizontal diameter, and current from a battery was passed through a variable resistance and an ammeter and across the pulley from brush to brush. The drop in E.M.F. across the two brushes was read on a voltmeter by potential leads soldered to the brushes themselves, so that thermo-electric effects were eliminated, and no brush-holder resistance was included. The resistance of the copper drum was negligible, but the resistance of some ½-inch length of carbon on each brush was included, as representing probable working conditions, and this has not been subtracted in the following readings. It amounts to 0·04 volts on the two brushes with a current of 60 amperes per square inch.

The carbons were supplied by Le Carbone Co., the best quality, called X, being used. It was a very dense graphitised carbon with a specific resistance of 0·00193 ohms, or about 1,200 times the resistance of copper. Common grades of brush carbon have usually about three times this resistance. It was by no means a soft carbon, wore slowly, and took a high polish.

Preliminary experiments showed that vibration would play an important part in the resistance, and in order to simplify the first tests, brush holders were used in which vibration would be as small as possible. A rigid frame was fixed to the bed-plate, and the carbons were soldered into short brass tubes, sliding in other tubes fixed to the frame, and being pressed on to the drum by helical springs. The inertia was therefore little more than that of the carbon blocks themselves, while sideways vibration was prevented by the close fit of the tubes. As the wear during the tests was small, only a quarter inch of carbon projected from the tube, and the guide-tube extended almost to this point. The area was 1 sq. in. in all tests, the same pair of carbons being used all through.

I.—Determination of Contact Resistance of Dry Carbons and Copper.

The first experiments were devoted to the conditions of dry (*i.e.*, unlubricated) contact. The surface was kept perfectly clean by a polishing pad continuously pressing on the drum. There was an indication that a slight coating of carbon dust was beneficial, causing a slight diminution in both fall of potential and friction. But as the clean surface was more definite this was preferred, and the effect of the carbon lubricant was too small to modify the results appreciably.

Readings were taken at speeds from 860 up to 3,300 ft. per minute and with pressures ranging from 7 to 46 oz. per square inch. It would cumber the paper to quote all the numerical results in full, and in general these will be embodied simply in curves giving the mean values of several sets of readings under the same conditions. Fig. 1 shows the relationships obtained. There are some irregularities which refused to be eliminated, but the general trend is unmistakable. Down to 18 oz. pressure the speed does not influence the result. With 12 oz. the effect is barely noticeable at 2,300 ft. per min., but is marked at 3,300. With 7 oz. the effect is seen at 2,300 ft. per min., but not at 1,430 ft. It is clear that the influence of speed is indirect, causing vibration, which reduces the efficiency of contact. This will be seen more clearly below, when vibration is purposely introduced.

Fig. 2 gives the mean values of these, eliminating curves affected by

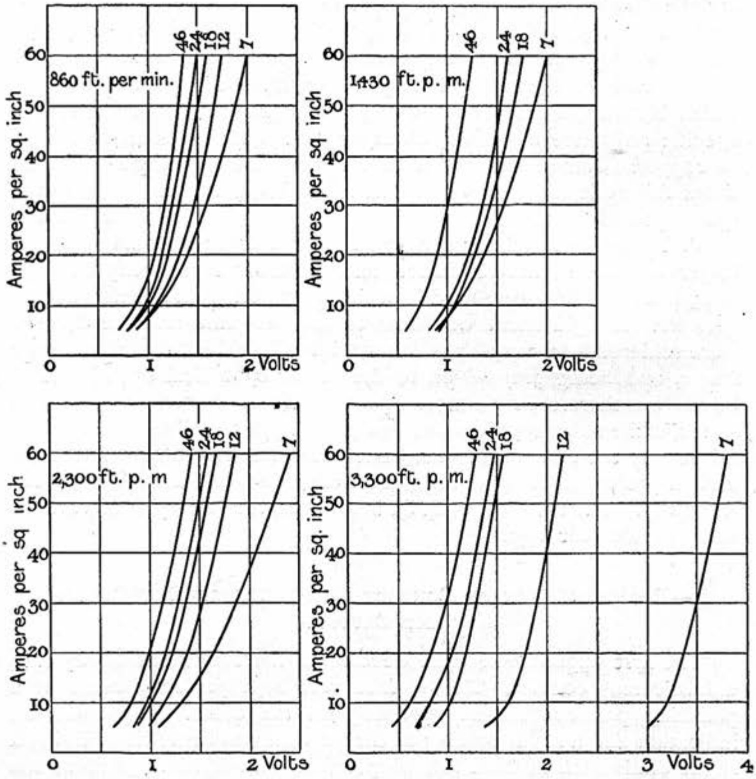

FIG. 1.—Effect of Pressure and Speed on Contact Resistances.

speed. Representing the mean of a large number of readings, it may be taken to portray the relation of E.M.F. and current for different pressures, when vibration is absent.

The curve may be expressed by the function $kE = i^{0.28}$. Assuming this index, and calculating the value of k for each point from 10 amperes to 60 at each pressure, the value of k given in Table I. is seen to be fairly constant for each pressure, and, except in the case of 7 oz., the irregularities show no regularity, so that this function expresses the ratio of E.M.F. to current with considerable accuracy, assuming that there is no vibration. Each vertical column is derived from the mean values of a number of sets of readings, the numbers being given in the last line.

TABLE I.—VALUE OF RATIO $i^{0.28}/E$.

i.	$i^{0.28}$.	Pressure in oz. per sq. in.				
		46.	24.	18.	12.	7.
10	1·90	2·26	2·02	1·90	1·70	1·75
20	2·30	2·28	2·04	1·93	1·70	1·69
30	2·57	2·25	2·06	1·96	1·70	1·65
40	2·79	2·28	2·04	2·00	1·73	1·60
50	2·98	2·28	1·98	2·00	1·75	1·59
60	3·10	2·22	1·99	1·99	1·73	1·55
Number of readings for each value ...		11	16	10	7	4

It is clear that the constant only, and not the form of the expression, varies with the pressure. Therefore any accidental imperfect bedding, which will remain constant through one set of readings, will not affect the form of the curve. But it is necessary to use only readings from well-bedded brushes in calculating the effect of pressure, and therefore the most reliable sets have been selected, and the mean values of k for different pressures have been found to conform very closely with the expression $k = 1 + 0·22\sqrt{P}$. In Fig. 6 is delineated this curve, with the ascertained values shown as points. The agreement is as close as can be expected. The full expression, between the limits 10–60 amperes and 7–46 oz., may be written with considerable accuracy—

$$E = \frac{i^{0.28}}{1 + 0·22\sqrt{P}}$$

to represent the relation of E.M.F., current, and pressure with a well-bedded brush free from vibration.

Doubt may arise whether a plain copper drum really represents a commutator. Assuming that the surface of the commutator is smooth, there seems no reason to doubt this, were it not for the fact, as will be shown later, that the current from the brush at each part fluctuates as it passes over a segment, the amount of fluctuation depending on the position of the part in the brush and upon the nature of the variation of the current in the segment. This matter will be examined in the last portion of the paper.

It will be well known to all that the actual surface of contact is often only a small proportion of the total brush surface, and it is interesting to examine what effect will be produced by imperfect bedding. Let the area be reduced to $1/n$ of its nominal value. Then the pressure per unit area and the current density are increased n times. The E.M.F. is changed to the value—

$$E \frac{i_n^{0.28}}{i^{0.28}} \frac{1 + 0.22\sqrt{P}}{1 + 0.22\sqrt{P_n}}.$$

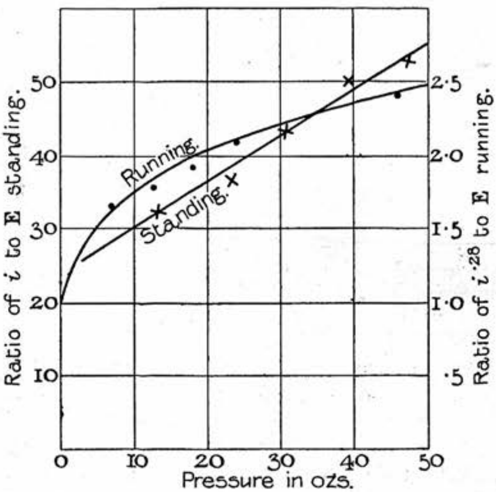

FIG 2.—Mean Values from Fig. 1.

Within large limits this factor differs very little from unity. For example, if only one-fifth of the brush is bearing, the increase of E.M.F. is not more than 5 per cent. Hence we see that imperfect bedding has scarcely any influence on the brush losses. It follows also that with a given spring tension and current the loss will be much the same whatever size of brush be used within reasonable limits, and that there is no advantage in using low current densities. Moreover, a small, and consequently light, brush with equal total pressure will vibrate much less, and will therefore be less liable to spark. The frictional losses will be also unchanged, for it will be shown later, what is indeed quite normal, that the frictional loss is proportional to the pressure. There will be a certain ratio between current density and pressure per unit area at each speed, at which losses are a minimum, the ratio being kept low at low speeds and high at high speeds. The curves in Fig. 3 show the total losses in watts per ampere collected, plotted against current density, for various pressures and speeds, the values being taken directly from the curves in Fig. 2, and the friction constant being 0·0005, for which see later. It will be found that when horizontal lines are drawn through, representing a constant loss, the ratio of current density to pressure is approximately constant. At a high speed, say, 3,000 ft. per minute, the 7 oz. pressure is the most economical with a c.d. of 30, or a ratio of 4 to 1, while at 500 ft. per minute we may use 7 oz. at 9 amperes, 18 oz. at 24 amperes,

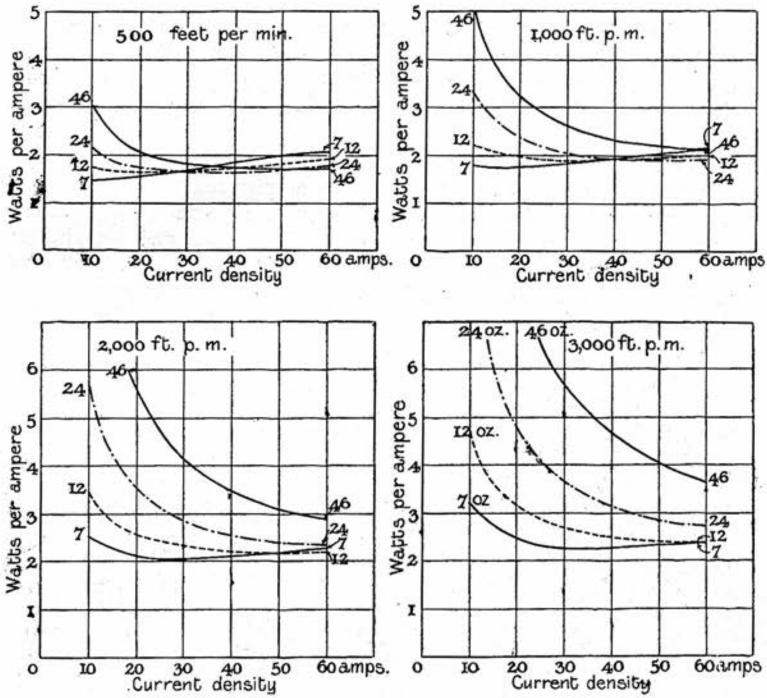

FIG. 3.—Total Losses per Ampere Collected, for various speeds, pressures, and current densities.

or 24 oz. at 32 amperes with nearly equal minimum loss, or a ratio of 1·3 to 1. Of course these conclusions will be modified by considerations of sparking, and it may not be possible at high speeds to use the most economical ratio.

Mr. Hobart ("Electric Generators") mentions 40 amperes as a safe limit, and 20 oz. as good practice, or a ratio of 2 to 1. If the curves of total losses are examined for the point corresponding to 40 amperes and 20 oz., it will be seen that there is not much wrong with these values, except at the highest speed, and here a lighter pressure and a greater current density might produce sparking. It is, indeed, satisfactory to find that over a wide range of speed, pressure, and current density a low value of total losses can be obtained; but there is a heavy penalty if these limits are much exceeded. There is no advantage in using a low current density, and in order to obtain the best conditions over all loads of a dynamo, the current density at full load should be fairly high, a few well-designed brush holders being better than a number of cheap ones, especially at high speeds, where a low current density is extravagant.

Corresponding tests were carried out with the S quality of carbons from the same maker. This is harder and less graphitised than the X quality, and its specific resistance is three times as large. It may be taken to represent an average hard grade of good quality. Owing to the greater hardness, it was a matter of some difficulty to obtain good bedding, several hours of continuous running producing little effect, even after the most careful preliminary rubbing down with fine emery paper. To facilitate bedding, the area was reduced to half a square inch, but the contact was never quite complete. The carbons tended to scrape when the surface was kept polished by a pad, and better results were obtained when the rubber was omitted, the E.M.F. being more consistent and of lower value. The tests were taken with the drum well warmed, each series being completed as rapidly as possible in order to maintain an approximately constant temperature through the set.

A group of readings gave very consistent results, the successive sets not varying more than 1 per cent. from the mean value; but when repeated at a later date the readings, though equally consistent among themselves, differed considerably from the former values. Fig. 3A shows the results on two different days, I. and II. being taken on one day at 40 and 60 oz. per square inch respectively, III. and IV. being the same taken at a later date. The logarithms when plotted lie very closely in straight lines, and the function is of the form :—

I. E is proportional to $i^{\cdot 58}$.
II. E " " $i^{\cdot 56}$.
III. E " " $i^{\cdot 44}$.
IV. E " " $i^{\cdot 41}$.

On each day the curves agree fairly well, but some change in conditions has made a considerable alteration in the form of the curve. The mean of all the readings, some thirty sets in all, gives a curve of the form $E = k\,i^{\cdot 5}$, which is very different from that obtained with X carbons, and the difference is important in the process of commutation. More prolonged experiment is required on various qualities of carbon, but it is clear that the contact resistance does not vary much for a large difference in specific resistance, and that the law of variation of E to i is not the same for different qualities.

Reference must be made here to a paper by Professor E. Arnold *

* "Über die Untersuchung von Dynamobürsten," *Elektrotechnik und Maschinenbau* July 29, 1906, abstract in *Electrician*, Vol. 58, 1906, p. 14.

which deals with the same subject. The materials examined were X and Z quality Le Carbone carbons, and except that the drum was of brass instead of copper, and that the E.M.F. was observed between a single brush and drum, the method of testing was similar. When a long period of time elapsed between each reading, so that the temperature of drum and brush was individual for each value of the current the E.M.F. for the two brushes reached a value of 1·1 volt for Z and 0·9 volt for X carbons at a current density of some 70 amperes per square inch, and as the current increased beyond this figure the E.M.F. rather diminished. We have not found this to occur in our experi-

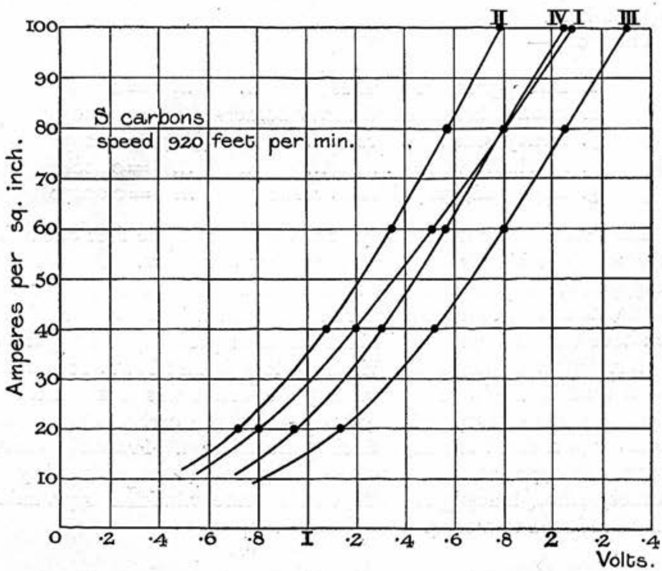

FIG. 3A.

ments, and while change of conditions often appeared to affect the readings, in the end, after repetition, little actual alteration was discovered. Professor Arnold also took sets rapidly, and obtained curves almost identical with ours. It is of interest that in these last readings he used a commutator instead of a drum.

Some other experiments and conclusions drawn from them by Professor Arnold will be discussed in the last portion of this paper.

II.—Friction of Carbon Brushes.

The friction was measured by reading the power absorbed by the driving motor when the brushes were on and off respectively, the readings being taken immediately after the E.M.F. readings at every set. For convenience, the power wasted in friction has been expressed by the formula $W = \mu\, v\, P\, A$ watts, where—

v = velocity in feet per second.
P = pressure in ounces per square inch.
A = area in square inches of both brushes.

The co-efficient μ shows some variation, but the divergencies from the mean do not point to any modification of the above formula. The value obtained with the above-described brush holders and a polished surface, as a mean of 18 readings, was $\mu = 0{\cdot}00065$. Values were also obtained when other brush holders were used, which may conveniently be given here.

Value of μ—

1.	Direct-pressure brushes	= 0·00065
2.	Padded brushes and heavy holders ...	= 0·00050
3.	Heavy brush holders	= 0·00037
4.	Parshall's value	= 0·00043
5.	Raymond, graphitised brushes ...	= 0·00070

The agreement between Raymond's value and the first one is fairly close, and possibly his brushes were softer than ours. The value with heavy holders is low, and this is doubtless due to the vibration. An examination of Mr. Moore's experiments, from which Mr. Parshall takes the above value, shows that his brush holders probably had a good deal of vibration, and hence the frictional loss is also low. It should be added that in the case of 2 and 3 the drum was not continuously polished, and, as has previously been stated, the carbon dust acts as a lubricant to a small extent, reducing the friction. Probably the value 0·0005 will represent the usual working conditions with fairly hard brushes, although at high speeds, where some vibration is probable, it will be reduced to 0·0004.

III.—Experiments with Lubricated Brushes.

It is a common practice to use some lubricant, which generally contains hard paraffin wax as the basis. To examine what influence the lubricating film exerts on the E.M.F., a set of readings was taken with the same brushes and holders as in Series I., but lubricating the drum with paraffin wax. It was not so easy to ensure uniformity of lubrication as uniformity of cleanliness, particularly with a solid or pasty lubricant. When first put on, the lubricant causes sparking and a rise in the E.M.F., and a consistent condition is obtained only after the wax has become softened and uniformly spread. Therefore continuous application was not possible, and some variations were inevitable in the quantity of lubricant on the surface. This made less difference to the E.M.F. than to the friction. The temperature of the surface affected the viscosity of the wax, and on a cold surface the effect was not satisfactory. This, however, is not likely to occur in practice, and in the tests the drum and brushes were warmed up by a large current before readings were taken.

Fig. 4 shows a complete series taken at 2,300 ft. per minute, and it will be seen that the lubricant has produced very little change in either the shape or the value of the curve, until the pressure is reduced to 18 oz. Below 12 oz. the readings were irregular, and the E.M.F. rose rapidly, showing that there was imperfect contact. The speed exerts considerable influence on the E.M.F. Even at a pressure of 42 oz. there is a continuous change between 1,200 ft. per minute and 3,300. At 1,200 the E.M.F. was exceptionally low, whereas at 3,300 the value is nearly doubled. With a dry surface (Fig. 1) there was no change at all.

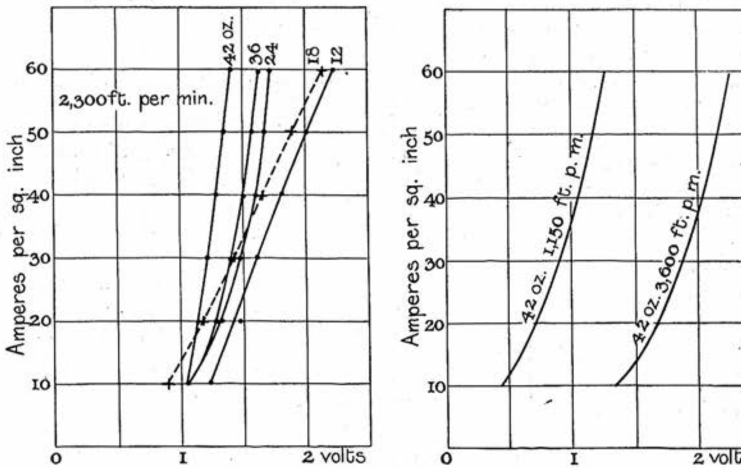

FIG. 4.—Tests with Lubricated Surface.

The frictional loss was determined at the same time, the following values being obtained :—

Pressure	12	18	24	36	40	42 oz.
$\mu =$	0·00013	13	15	074	065	10

or a mean value of 0·00011 watts per oz. per foot per min. per sq. in. The values given above show rather wide divergencies, due to differences in temperature and thickness of lubricant, but in all cases the value is much lower than that found with a dry surface.

Two special commutator lubricants were also applied, one a mixture of paraffin and graphite, the other apparently consisting of powdered paraffin with a little soapstone, coloured and scented with unimportant constituents. The results were much the same as those obtained with paraffin wax alone, though it is possible that with an ungraphitised brush the addition of graphite in the lubricant may be beneficial.

Several liquid lubricators were tried, applied continuously by a pad against the drum. Among them were light engine oil, paraffin oil, and toluol. None were advantageous. The thinner lubricants somewhat increased the E.M.F. and made little difference to the friction, while the engine oil rapidly clogged and increased the E.M.F. considerably.

The results of the tests with paraffin wax are remarkable, and were certainly not expected by the authors. The curve at 1,200 ft. per minute (Fig. 4) is the mean of six sets, all agreeing closely, so that no accidental error was possible, and it will be seen that the values are as low as any obtained with the dry surface. The lubricant, although an insulator of enormous resistance, permits the passage of large currents with absolutely no interference, and yet is present in sufficient thickness to reduce the friction to one-fifth of its value for dry surfaces. This is an attractive subject for discussion, but one which cannot be entered upon here. It may be added that when the drum was stopped, the resistance was very irregular, and it generally rose to what was practically total insulation.

Whatever the explanation, there is no doubt that the action of the lubricant is beneficial in reducing friction and wear and tear of brushes, without any counterbalancing increase in electrical losses, provided a little attention is bestowed on it. On account of the reduction in friction losses the pressure may be increased to some 30 or 40 oz., and over a large range of current density current can be collected at a total loss of less than 2 watts per ampere. The data are scarcely adequate for precise calculations, and we shall not attempt any formula connecting E.M.F., current, speed, and pressure, which would doubtless be much affected by the degree of lubrication; but the general character of the phenomena and their practical application are sufficiently clear.

IV.—Effect of Vibration.

The influence of vibration has already been noticed at high speeds. To examine this further, brush holders were made in which there was a considerable tendency to vibration—long arms pivoted at one end and possessing more inertia. The same brushes were used. There is no need to enter into details, as the tests only show what to avoid.

Fig. 5 shows the results. At 580 ft. per minute there was no vibration, and the values of E.M.F., even down to 12 oz., correspond closely with the previous values. At 1,600 ft. the effect is marked, at 2,300 still more marked, the increase showing at a pressure of 55 oz., while at 3,200 ft. the E.M.F. runs up to nearly 9 volts. Although the collection at this speed was not sparkless, it would scarcely have been deemed very bad on a dynamo. At these high speeds the collection is clearly almost entirely through the arc, as the E.M.F. is almost constant between 10 amperes and 40, and it is remarkable that the readings were exceedingly consistent, repeated sets not varying more than some 3 per cent.

The vibration was reduced by inserting pads behind the carbons,

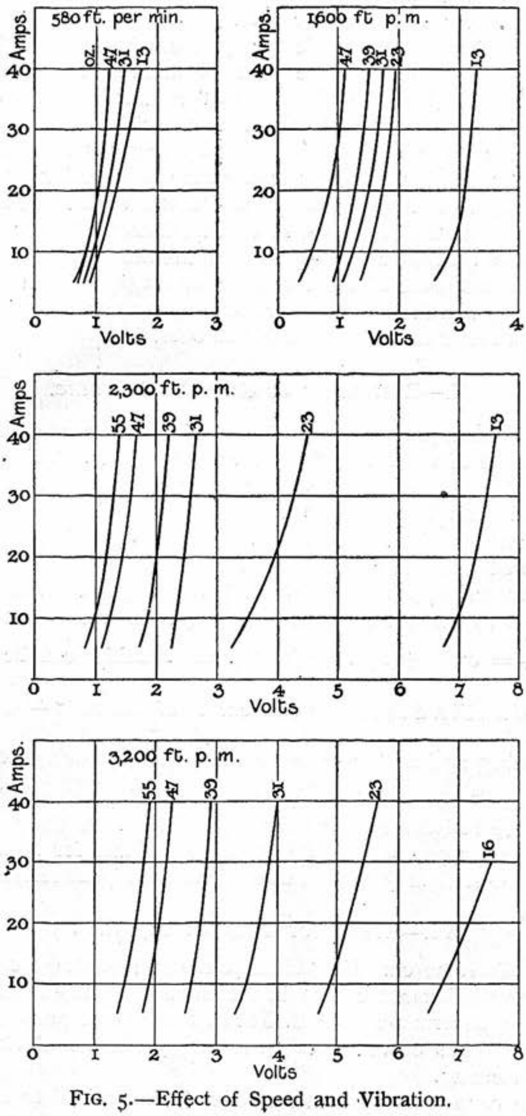

FIG. 5.—Effect of Speed and Vibration.

and a marked improvement was noticed. At 1,430 ft. per minute the E.M.F. was still normal, at 2,300 ft. it was normal down to 16 oz., but at 3,200 ft. it was barely normal even at 42 oz. It is scarcely necessary to reproduce these curves.

It will be noted that the effect of pressure is twofold. It reduces vibration, and it improves the actual contact independently of any vibration. As has been pointed out, the efficiency of collection is improved by keeping the pressure low, especially with dry surfaces; but the reduction must stop sharply at the point where the particular brush holders in question show a tendency to vibration, or losses will run up rapidly. It is important to notice that the E.M.F. maintains a high value with small currents, so that an increase in brush area will not eliminate the loss, unless, by subdividing the brushes, a probability is obtained that some of them will be making good contact. These results strengthen the opinion expressed above, that a few well-designed holders are better than a number of bad ones.

V.—Resistance of Brushes Standing.

Though not a practical condition, it will be interesting to examine the resistance of the brush contact when standing. This was determined during some of the tests, after stopping the drum. The current was raised from 10 to 60 amperes as before, and while occasional abnormal values of E.M.F. were obtained, the readings for the most part showed that the ratio of E.M.F. to current was constant for a given pressure, and that Ohm's law holds good. The resistance diminished as the pressure increased, and the conductance may be written $\frac{i}{E} = 0{\cdot}6\,P + 24$, though no great reliability can be placed on the formula. Fig. 6 shows the two curves of the ratio $\frac{i}{E}$ standing and $\frac{i^{0\cdot28}}{E}$ running, against the pressure, the latter producing considerably more effect on the standing than on the running values. With small currents the resistance of the running contact was the greater; but between 60 and 70 amperes the curves cross, and for higher current densities the stationary contact would have the higher resistance.

VI.—Effect of Time on the E.M.F.

To obtain some clue, if possible, to the curious shape of the curve E/i, some variations were made in the mode of taking readings, in the direction of ascertaining the E.M.F. at the earliest possible moment. For the previous curves were all taken with a liberal allowance of previous running.

1. The current was kept at zero, suddenly raised to a particular value, and the E.M.F. read as rapidly as possible.

2. The E.M.F. was read by a ballistic galvanometer and condenser when the current was switched on.

3. The E.M.F. was read by a ballistic galvanometer as in No. 2, but the galvanometer circuit was automatically opened a small fraction of a second after closing the main circuit, thus eliminating the effect of any subsequent change.

Readings were taken at 24 oz. pressure and 1,430 ft. per minute. To avoid cumbering this paper with too many curves, it may simply be stated that all three methods gave closely the same curve, and the mean of them all agreed almost exactly with the normal running curve at that speed and pressure. The curve of No. 3 method gave slightly lower values of E.M.F. than the others, but the difference was not sufficient

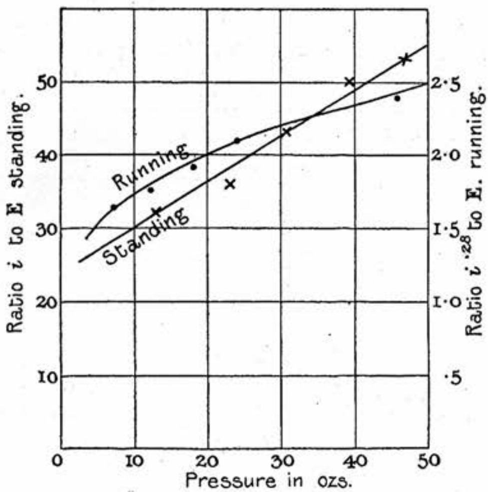

FIG. 6.

to bear any deductions. It may be taken, therefore, that the E.M.F. assumes this value in an exceedingly short space of time.

The form of the curve of E/i is strongly suggestive of the shape of the curve obtained when a glow lamp is heated, but the experiment with method 3 shows that any heating must be confined to an extremely thin layer of carbon, on account of the rapidity with which it takes place. There is also the difficulty that stationary brushes do not exhibit this phenomenon, but obey Ohm's law, so that the mere fact that the contact takes place at comparatively few points, with consequent enormous current densities for a short distance, does not seem a satisfactory explanation, for some similar effect should be shown in the stationary brush. We confess our inability to suggest a theory explaining the law of variation of the contact resistance.

VII.—DETERMINATION OF SPARKING E.M.F.

The next part of our experiments was devoted to determining the E.M.F. between the brush and the commutator segment at the moment

Cleghorn's experiments begin here.

of separation, which we may call the sparking E.M.F., or the E.M.F. due to a sudden cessation of current in an inductive circuit, which tends to produce a spark at the point of separation. This has no connection with the reactance E.M.F. embodied in various formulæ, which deal with the value of L^{di}/dt before the break, and assume that the current has already become zero when the separation occurs. The sparking E.M.F. is therefore a measure of the failure of the machine to commutate its current in the correct manner. That this does not necessarily mean that the machine is commercially unsatisfactory is obvious from the fact that in forced commutation with fixed brushes the ideal procedure must be departed from, and we shall examine whether the conditions for reducing the inevitable sparking E.M.F. are the same as those producing an ideal commutation under the ideal conditions. We shall also examine the value of the currents circulating in the short-circuited coil, and their effect on the sparking E.M.F. and the magnetic field of the machine.

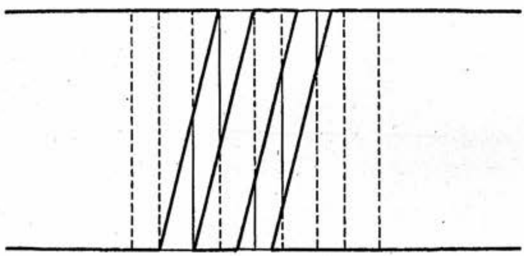

FIG. 7.

As interest is now particularly directed to the use of machines with commutating poles, this type was examined with the greatest fulness, and for comparison similar readings were obtained from a simple machine.

The machine was a 15-h.p. 4-pole enclosed motor with two-circuit wave-wound slotted armature. At 460 volts with the full exciting current it ran at 550 revolutions per minute. The armature has 1,384 bars and 173 commutator segments, with four turns per section, 29 slots with three outward and three return sections in each slot. The reactance E.M.F. calculated by Hobart's formula, if the effect of the commutating pole is neglected, is 3·5 volts. The four brush arms each carry two brushes 1 in. long and $\frac{7}{16}$ in. broad. The commutating poles had a narrow pole face $\frac{7}{8}$ in. broad, but both main and commutating poles slanted across the teeth, so that the total span was 2 ins., or nearly two slots and two teeth, as shown in Fig. 7. The makers were the Morris Hawkins Company.

The E.M.F. was measured on a high-speed falling-plate Duddell oscillograph, which was connected as a voltmeter between the brush and a trailing spring attached to the back of the brush, and separated from it by a sheet of mica $\frac{3}{64}$ in. thick. While both brush and spring were touching the same segment the oscillograph registered the fall of E.M.F. from carbon to segment, but as the carbon left the segment, the induced E.M.F. caused a current to flow through the instrument to the segment just left. As the spring traversed the mica between the segments the circuit was broken and the deflection fell to zero, but in many cases the brush bridged this, and the E.M.F. merely dropped to the first value. The use of a circuit in parallel with the break tends to reduce the E.M.F., but in most cases the resistance was some 160 ohms, so that a very fair idea of the sparking E.M.F. was obtained. The direction of the E.M.F. indicates whether the current is from brush to segment or the reverse, and indicates whether the machine is under-compensated or whether over-compensation has set up a circulating current in the reverse direction. In the following diagrams the direction above the zero line indicates an E.M.F. in the direction of the main current, or under-compensation.

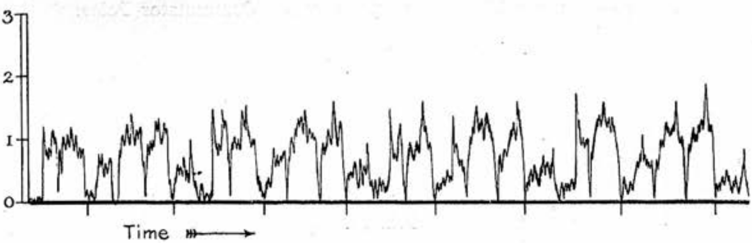

FIG. 8.—Running Light: Slow speed (150 revs.).

As the speed which was used in some of the tests, 870 revolutions per minute, involves 2,500 commutations per second at the brush, the resolving powers of even an oscillograph were severely taxed, and the waves are unavoidably much crowded. Further resolution by increasing the speed of falling was prevented by the weakening of the photographic trace. But for the most part it was only the height of the wave that was required, and a large number of waves gave a better value of the average E.M.F. required. In order to make sure of the action of the apparatus a slower speed was adopted at first. Fig. 8 shows the action at a speed of 150 revolutions when the motor was running light. The waves are quite distinct, falling into groups of three, the number of coils in a slot. The E.M.F. rises as the slot travels to the approaching pole piece out of the field of the commutating pole. The zero values show the mica separators, after which there is a rapid rise to the E.M.F. between brush and segment, followed by another rise as the brush leaves the segment. There is much irregularity of detail, and it can scarcely be expected that the currents will repeat with exact regularity. There are six ripples on each wave for which more than one cause can be suggested, and it would be unprofitable to follow them out in detail. The machine is under-compensated, and the sparking E.M.F. rises through the group of three coils as the compensating pole becomes weaker. The maximum E.M.F. is only 1·7 volts, as the speed is very low, the E.M.F. between brush and segment being about 0·8 volts. The compensating poles were excited with more current, the motor still running light,

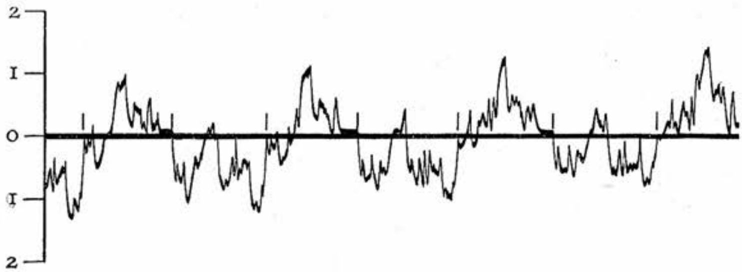

FIG. 9.—Running Light: 6 amperes round Commutator Poles.

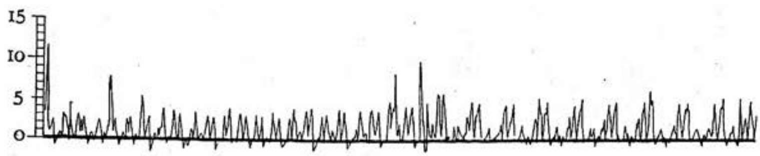

FIG. 10.

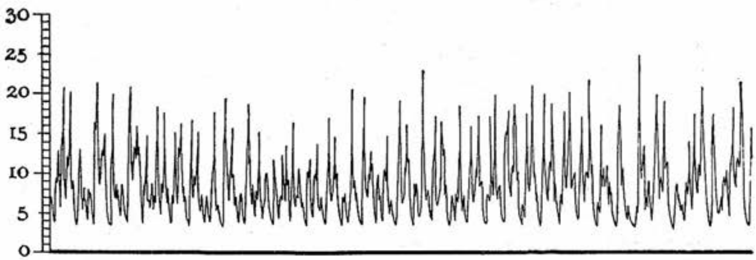

FIG. 11.

and the curves showed a gradually increasing over-compensation. Fig. 9 was taken with 6 amperes, the armature current being 2 amperes, and much of the E.M.F. is now in the reverse direction. In fact, the waves group themselves in two sets of three, and in alternate sets the current is entirely in the reverse direction, the other parallel brush arm probably taking the driving current during this interval.

Repeating with different loads and the proper compensating current for each, the E.M.F. showed always under-compensation. This will be examined in more detail at a higher speed.

The motor was intended for a large range of speed, and we may therefore pass over the tests at normal speed, to examine its behaviour under the more trying conditions of a high speed and a weak main field. A speed of about 870 revolutions per minute was arranged, and Fig. 10 gives the light load values with an E.M.F. of 6 volts, Fig. 11 the full load values, in which the E.M.F. rises to 20 volts. The motor is considerably under-compensated, but nevertheless the brush dealt with this high E.M.F. with very little visible sparking, the mass of cold copper and the speed of separation doubtless contributing to this

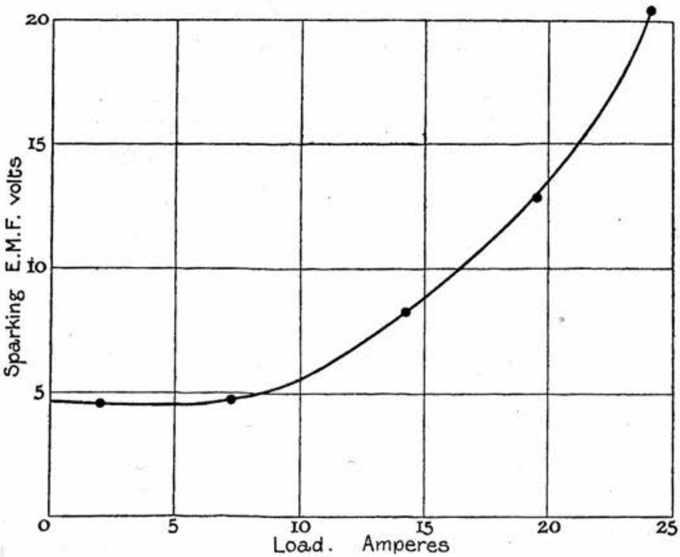

FIG. 12.

result. Fig. 12 shows the set of values obtained at these and at intermediate loads.

Further tests were made with no current round the compensating poles. The sparking was considerable, and even on half load the sparking E.M.F. rose to 32 volts. By shifting the brushes the current was taken up to full load with a sparking E.M.F. of about 32 volts. This is, of course, an abnormal condition, for the commutating poles were not removed, and their presence over the coil under the brush produces a strong magnetic field, due to the armature, which passes through the coil and naturally produces large circulating currents. The value of these will be examined later, and their magnitude easily explains this great E.M.F.

It had been in the mind of one of us that a brush with a trailing edge in the form of a very blunt **V** would act beneficially in reducing the current before the final break, and this seemed a suitable method for testing the device. The result, however, was not favourable, for the sparking E.M.F. was very little diminished. We have not followed up this method of testing different qualities and shapes of brushes, but it appears to be capable of much useful employment.

The foregoing experiments indicate that where the conditions assumed in the reactance formulæ are not fulfilled, it is important to determine whether the sparking E.M.F. will be large. At the same time they show that it need not be very small. In all cases of forced commutation, *i.e.*, where the current does not die down to zero by the action of a suitable E.M.F. in the short-circuited coil, but is merely throttled by the decreasing area of contact between segment and brush, often in spite of an E.M.F. in the coil tending to keep it up, in all such cases there will be an abrupt break and a possible spark. In many cases the main current will be unimportant, and the value to which the induced circulating current has risen will control the smoothness of the commutation. A broad brush will be a positive harm, as allowing the coil to come more into the field of the wrong pole, and giving time for the current to rise. The value of the current will be proportional to this field, to the speed of the machine, and to the number of turns in the coil, for the resistance of the coil itself will usually be small compared to the brush contact resistance. The E.M.F. produced by breaking this current $= L\, {}^{di}/dt$, where L is proportional to the square of the number of turns (if they are all in the same slot), so that the sparking E.M.F. is proportional to the cube of the number of turns in the coil and the square of the speed. But the whole coil between two adjacent segments is not involved, if there are more than two sets of brushes, for the different sets break circuit successively, and the parts between the other brushes will readjust their currents without a spark. Hence the commutation is more easily forced in multipolar machines than in those with only two poles. To test this, the sparking E.M.F. was determined with one brush on each of the four arms, and again with two brushes on two arms. In the first case the E.M.F. was 8 volts, in the second 15 volts, or nearly twice as great, the length of bar in which current is stopped being twice as long.

The same result is shown in the oscillograph curves of the current in the short-circuited coils shown by J. K. Catterson-Smith.* Using several brushes, he found the current change its value by successive small steps instead of one large one, from which it may be concluded that there will be less tendency to spark.

The above estimation of the sparking E.M.F. assumes that the decrease of current, due to the diminishing area of the segment in contact with the brush, is sufficiently rapid to produce a sensible E.M.F. in the coil. But if this is not the case, and the self-induced E.M.F. does not appreciably influence the current, then the sparking E.M.F. will be proportional to the current at the moment of breaking,

* *Journal Institution of Electrical Engineers*, vol. 35, 1905, p. 430.

to the coefficient of self-induction, and to the speed or Lni, which is similar to the reactance voltage except that i has only a remote connection with the armature current, and depends on the resistance of the brush contact and the E.M.F. induced by the stray field. If it is possible to find a quality of carbon in which the resistance is fairly independent of current density the use of such brushes should sensibly decrease sparking.

For forced commutation it is preferable to have as small a magnetic field as possible in the interpolar space, to diminish the circulating currents. Hence a narrow air-gap and a large interpolar space are beneficial. Distortion of the field is then of little consequence, and weakening or even reversing the pole tip will not matter, so long as the field from the strengthened pole tip does not come down on the coil. The ideal machine with commutating poles does not experience forced commutation, but with incorrectly adjusted poles some forcing of the current is inevitable, and the larger inductance will cause sparking.

As a comparison with the foregoing curves, some tests were made on a simple motor without anti-sparking devices. The machine was a 6-pole, 55-h.p. motor made by Mavor and Coulson, running normally at 500 revolutions with 460 volts on the brushes. The pole shoes were square and the air-gap rather small for the size of the armature, being 3·9 mm. The slot breadth was 9 mm. and the breadth of the top of the tooth was 10 mm.

There were 282 turns with 142 commutator parts, or two turns per coil, wound in a two-circuit winding. There were six pairs of brushes, each of $1\frac{1}{8}$ sq. in. area. The nominal maximum current density was therefore 15 amperes per square inch.

As this machine was fitted with additional testing devices, which included a pair of spring contacts on the commutator, the contact resistance of the brush was eliminated by setting the two contact makers a short distance apart, the one just in front, the other behind the trailing edge of the brush. When they both touched the same segment the E.M.F. fell to zero, and the peaks of the curve read the E.M.F. in the coil as it left the brush and received the main current from the new side. The potential brushes were set at a distance little more than that of the breadth of the mica between the segments, so that the reading just included the spark and no more.

Setting the brushes in the most favourable position for running light, the curves gave an E.M.F. of 3·5 volts at this load, which rose to 4 volts at half load. It was found that if the potential leads were set with a very small gap, so that the trailing contact moved on to the mica after a contact lasting only $\frac{1}{32}$ in., the E.M.F. curve rose abruptly and dropped to zero (Fig. 13). On increasing the time of contact, the zero drop was only momentary, with a rapid rise as before, but there followed a momentary dip as the sparking E.M.F. ceased, and a further rise showed the E.M.F. induced in the coil by the stray field (Fig. 14), which was cut short by the contact coming on to the mica. The first rise in Fig. 14 is the same as the rise in Fig. 13, and that this is smaller than the E.M.F. induced by the stray field shows how thoroughly the current is controlled by the diminishing area of brush contact.

The following values of the first rise were obtained :—

		Armature Current.		Sparking E.M.F.
Brushes set for light load	...	7 amp.	...	3·5 volts.
,, ,, ,,	...	23 ,,	...	3·5 ,,
,, ,, ,,	...	46 ,,	...	4·0 ,,
,, ,, 46 amp.	...	46 ,,	...	3·0 ,,
,, ,, 46 ,,	...	7 ,,	...	2·0 ,,
,, ,, 37 ,,	...	7 ,,	...	2·0 ,,
,, ,, 37 ,,	...	37 ,,	...	3·0 ,,
,, ,, 37 ,,	...	75 ,,	...	3·5 ,,
,, ,, 75 ,,	...	75 ,,	...	2·5 ,,

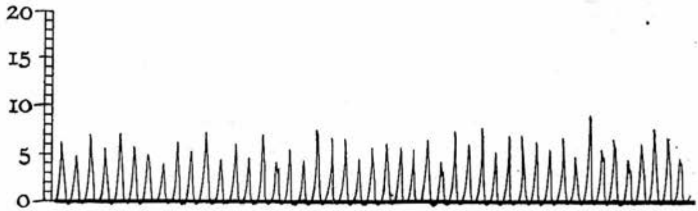

FIG. 13.

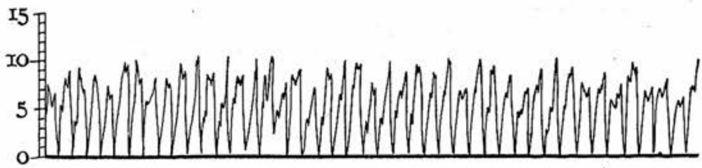

FIG. 14.

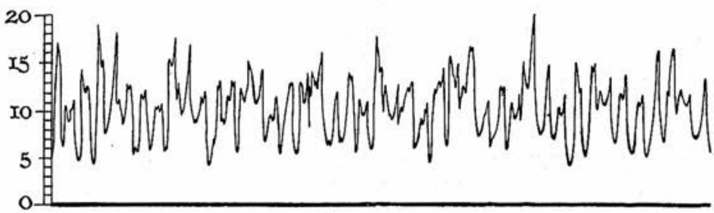

FIG. 15.

The E.M.F. given here is the mean of somewhat irregular values, as there is no doubt that small changes of brush contact at the last moment will readily produce variations in the sparking E.M.F. For example, a mean reading of 3·5 volts will range from 3 to 4, or in places to 5. It must also be remembered that the supposed best position for the brush is a point difficult to ascertain, and the whole shift is very small, so that the minimum values are not consistent.

Additional readings were taken by the earlier method, from brush to contact spring, under the same conditions as those for Figs. 13 and 14. The value of the first rise, so far as can be determined, is much the same as before, but the inclusion of the contact resistance has complicated the curve. During this time the zero value was rather changing, and the value of the contact resistance drop is probably exaggerated.

Without claiming any great exactness for these numbers, it is evident that the E.M.F. of self-induction, which tends to produce a spark, is very small in this machine, and variation of load and position of the brush does not create large changes. The machine has a very weak field in the space between the poles, for the air-gap is small and the distance between pole pieces is large. The number of turns per coil is small, the complete coil is divided into three parts by the brushes, and the speed is not high. There are therefore all the conditions for a very moderate sparking E.M.F. or good forced commutation, although the value of the reactance voltage is not especially low, being $3\frac{1}{4}$ volts. A further examination into the process of commutation of this machine will be considered below.

VIII.—Distribution of the Magnetic Field, and Influence of Circulating Currents in a Motor with Commutating Poles.

Readings of the magnetic field of the machine were taken by means of a search coil on the armature, connected through slip-rings to the oscillograph. Fig. 16 shows the field due to the main poles, and Fig. 17 represents the influence of the commutating poles, with the full current round the coils. Exciting these as for a motor, a series of curves was taken with increasing currents, and the resulting total areas, representing the magnetic flux, are shown in curve A (Fig. 18). It is clear that by half load the commutating poles are saturated, and the rapid rise of the sparking E.M.F. in Fig. 12 has already indicated that this was probable.

It has been shown by Messrs. Walls and Smith (*Electrician*, April 6, 1906) that in a stationary armature the magnetic flux of the commutating poles is independent of that due to the main poles, and it may be regarded as crossing the latter at right angles. These curves indicate that this is the case, for the effect is merely a hump on one side, the main portion being unaffected. The brushes were put down in the central position, and similar curves taken at different loads, the load current exciting the commutating poles. The brushes being central, there is no demagnetising action exerted directly by the armature current. The commutating poles are demagnetised by the magneto-motive force of the armature. There are powerful currents in the short-circuited coils, which produce violent fluctuations of magnetic field under the commutating poles, and which would tend to magnetise the main field. But the areas of the curves, which are plotted in line C, are almost constant, showing that the increased

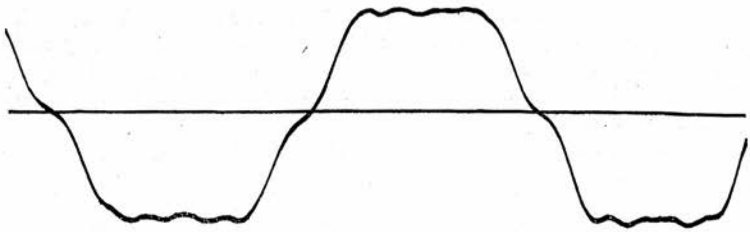

FIG. 16.—Armature driven externally. Brushes lifted. No current round Commutator Poles.

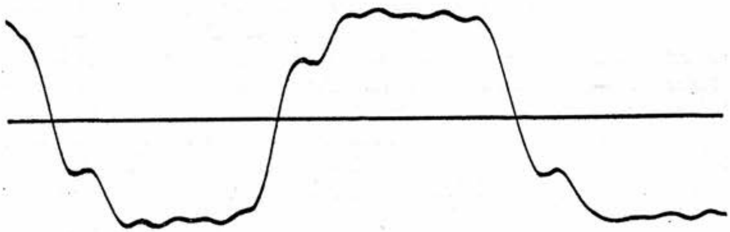

FIG. 17.—Armature driven externally. Current round Commutator Poles 28 amperes (full load current). Brushes lifted.

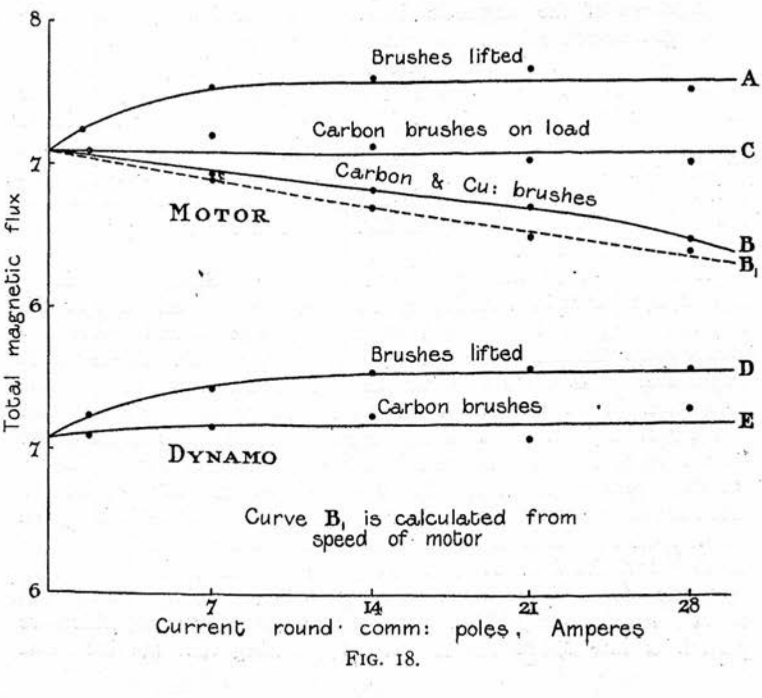

FIG. 18.

reluctance of the main circuit due to the distortion of the field has counterbalanced the increased M.M.F. Figs. 19, 20, 21 are examples of the curves obtained at light load, half, and full load respectively. The circulating currents steadily increase with the increase of load, as the reversed field under the commutating poles increases.

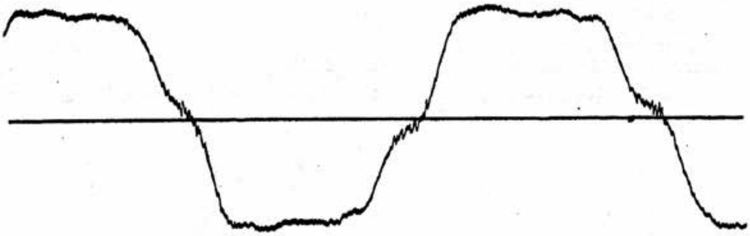

FIG. 19.—Field on Load. Running light : 2 amperes.

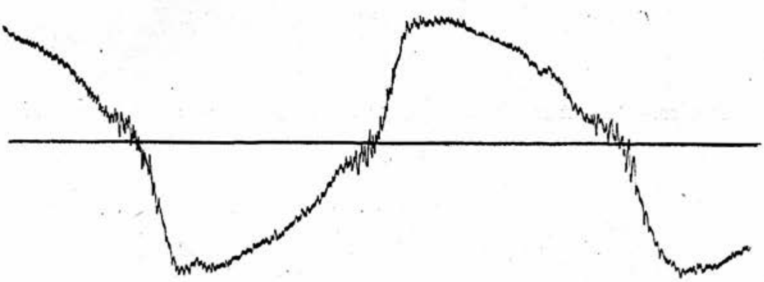

FIG. 20.—Half Load.

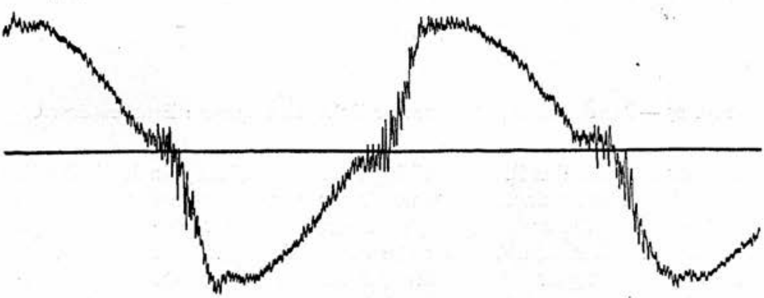

FIG. 21.—Full Load.

The same tests were carried out with copper brushes, but the sparking prevented the trial of heavy loads. The results were much the same as with carbon brushes, but the circulating currents were greater, as would be expected.

To examine the influence and magnitude of the circulating current apart from armature distortion, a series was taken with the armature running light and a separate current round the commutating poles, excited as for a motor. This gave a gradually increasing over-compensation. Figs. 22, 23 give the results with 14 and 28 amperes, and the magnetic flux for each is plotted in curve B, Fig. 18. The commutation being over-compensated, the short-circuit currents are in the reverse direction, and the total field is considerably diminished. As a check on the figures derived from the areas of the curves, the line $B_{,}$ was plotted from values calculated from the speed of the motor, and it will be seen that the correspondence is fairly close. Copper brushes gave very much the same results, the points lying practi-

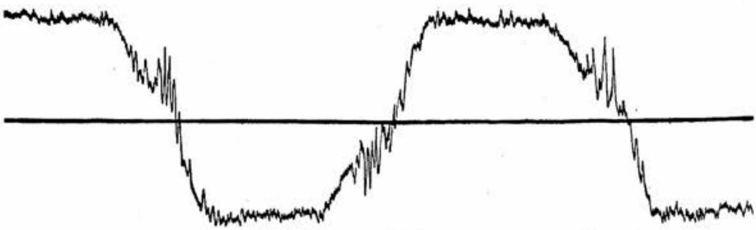

FIG. 22.—Current round Commutator Poles 14 amperes : Brushes down.

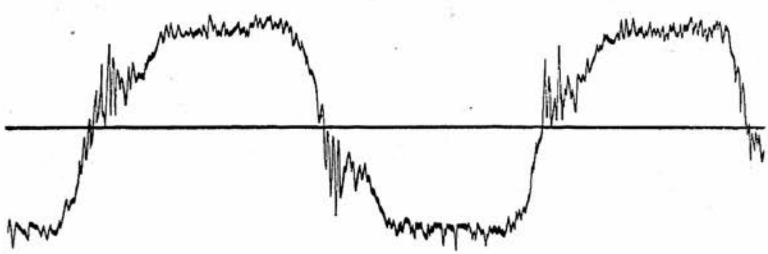

FIG. 23.—Current round Commutator Poles 28 amperes : Brushes down.

cally on the same line B. Examining the curves (Fig. 23) in detail, it will be noticed that in places the short-circuit currents completely demagnetise parts of the commutating poles, from which their value may be estimated. The M.M.F. across the gap at full load is 1,700, and the ampere-turns 1,350. There are for the most part two coils short-circuited under the brush, containing 24 turns, so that the current must amount to some 60 amperes, and its maximum value is probably much more in one of the coils. Their influence on the main field was determined by measuring the area, and the demagnetising effect was found to be some 10 per cent. Calculating from the characteristic curve, this represents 350 ampere-turns, the average value given by this method being much less than the maximum value given above. No doubt such large currents, several times the normal current, are not to be anticipated in a well-designed machine, but it is clear that there are great possibilities if the design is incorrect. The sparking E.M.F. obtained under the same conditions was found to be very large.

An attempt was made to use copper brushes, but the sparking and disturbance of the field were so violent that the motor began to hunt, and readings were impossible above a magnetising current of 7 amperes.

Another series was taken with the commutating poles excited as for a dynamo, *i.e.*, in the wrong direction. With the brushes lifted, so that no disturbance could take place, the values of line A were obtained again, as shown in D.

The brushes were then put down and the machine run as a motor. Line E gives the results, corresponding to line B. The short-circuit currents magnetise the main field, and the total flux rises as the current round the poles increases.

These curves in Figs. 19, 20, 21, confirm the deduction from the curves of sparking E.M.F., that the commutating poles are not sufficiently powerful, and they further show the great risk of such poles when incorrectly designed, for the reluctance of the magnetic circuit, in the air-gap of which the short-circuited coils lie, is small, and a small want of balance of magneto-motive forces will produce a considerable magnetic field. By using such poles the maker expects to be able to allow a large number of turns in the armature coil, and the liability of sparking is increased, in addition to the disadvantage of the heating effect of the short-circuit currents on armature commutator and brushes, and the loss of power. In the simple machine there is much less danger of unsatisfactory commutation.

It is only fair to the makers of the motor to state that this particular machine was one of the first they had made, and it should be added that, notwithstanding the errors revealed in these tests, the motor runs with little sparking even at high speeds.

The risk of using too broad a brush is also clearly brought out. These should be as narrow as possible, in order to curtail the time during which extra currents can be produced. Whether under or over compensated, the motor will tend to spark if the brush is broader than is absolutely necessary, and as we have seen in the first part of the paper, a high current density makes little difference to the commutator losses.

In Mr. Creedy's paper (*Journ. Inst. El. Eng.*, April, 1905), among experiments on an alternate-current series motor, is one on a direct-current series motor, in which he measures by a falling-plate oscillograph the fluctuations in the magnetic field and the armature current, finding ripples in the magnetic field and the current. He attributes this, in part at least, to variations of brush resistance, and with a series motor such an explanation is possible ; but it was much more probably the same action that has been noted above. Mr. Punga, in the discussion of the paper, suggests that short-circuit currents may be the explanation.

IX.—Measurement of Current in the Segment under the Brush.

The foregoing experiments gave only indirect information concerning the current flowing into the brush from a segment, and so far as we know, no direct measurements of the rise and fall of the current in a segment have been made. As the current in a segment endures for an extremely short space of time, either an oscillograph or a contact-maker must be used. The resistance of the lug itself is too small to permit of a reading of the fall of potential, but a resistance inserted for the purpose would tend to divert the current into adjacent lugs also in contact with the brush. Accordingly three consecutive segments were provided with a resistance of 0·018 ohms, and readings were taken from the central one. The current is then unaffected, except that the total armature resistance is momentarily increased by some 5 per cent., which will not sensibly influence the result. Currents in the short-circuited coils will be reduced, but the dimensions of these will vary so much between one machine and another, and with the width of the brushes, that their exact value in the particular motor examined is not of great importance. The resistance was arranged primarily for use with an oscillograph, which method was abandoned, and it was unnecessarily large for the method finally adopted.

The contact-maker method consisted in charging a condenser with an E.M.F. at a particular instant by means of a pin and spring. On the terminals of the condenser was a galvanometer, which with a very small consumption of the charge gave the E.M.F. The loss of charge was only 6 per cent., or the average E.M.F. 3 per cent. below the value to be measured. The readings were standardised in two ways: (1) by placing a standard cell directly in the galvanometer circuit; (2) by placing the cell in the contact-maker circuit in lieu of the potential to be measured. The two readings agreed to 0·2 per cent., showing that no errors crept in at the slip-rings. For measuring the current in the lug, potential leads were taken off to a slide-ring and to a contact pin, and from these to the condenser. The E.M.F. between brush and segment was read in the same way, the pin being fixed in the segment, and a change-over switch brought either into action. The positions of the contacts were adjusted to give readings at nine points, dividing the distance through which the segment was in contact with the brush into eight equal parts. The whole circuit was carefully tested for leakage and found to be perfectly sound.

The machine examined was the 55 H.P. motor previously used. Although this has six poles and three brush arms in parallel, it was thought desirable to avoid complications, and only one brush arm was employed. Otherwise nine lug resistances would have been needed, and three simultaneous readings of current by three complete sets of apparatus. Though much interest would attach to the determination of the respective currents in the three parallel circuits, this part must be left to the future.

The use of a single brush arm made advisable a restriction of the current to half load, although with the brush in the most favourable position a greater load could have been carried. The brush area was 2 ins. axially and nominally $\frac{3}{8}$ in. circumferentially, which was reduced actually to $\frac{5}{16}$ in. The brush width was barely more than the width of a segment and mica strip, so that not more than two segments were active together. The brush pressure was 40 oz. per square inch, the high pressure rendering steady readings more probable. The full exciting current was used, and a pressure of 460 volts gave a speed of 480 revolutions per minute, which was maintained all through. The brush examined was the negative, current passing from segment to brush.

Readings were taken with the brushes central, set back, and set forward, with currents of 7, 25, and 45 amperes at each position. Repetitions of readings showed some changes in the form of the curve, which would be to some extent influenced by changes in the brush contact, and as each set of readings occupied about an hour, it is probable that such changes occurred even during a single set. The most consistent examples are shown in Figs. 24, 25, and 26. [In Fig. 24 the current is 35 amperes, not 25.] It will be noticed that the current does not start until after the first division, due to the leading edge of the brush being slightly bevelled, as was found afterwards. The upper curves show the three currents, the lower curves the corresponding E.M.F.s between brush and segment, and the central diagram gives as ordinates the contact area between brush and segment at each point. For a short space in the middle the whole segment is in contact with the brush, reducing to zero on either side, where the current begins or ceases.

The first rise of the current is extremely rapid, amounting in the curve 45 in Fig. 24 to a rate of increase of 200,000 amperes per second. If this is multiplied by the inductance of the coil in which this change takes place, the result is an E.M.F. of 5 volts, the counter E.M.F. in the short-circuited coil. Referring to the E.M.F. curve, it has a value in the coil just before contact of 7 volts. This is the E.M.F. due to the leakage field. The E.M.F. drops promptly to about 1 or $1\frac{1}{2}$ volts, the rest of it being used to overcome the counter E.M.F. in the coil, so that the slope of the current curve is closely in accordance with this E.M.F. In Fig. 25 the E.M.F. and rate of increase of current are almost as great, but in Fig. 26 the E.M.F. is very small, and the rate of rise of the current is much slower. But this E.M.F. is not the only cause of the current entering the new segment, for in that case the rate of rise would be the same for all currents. The resistance of brush contact in the previous segment forces the current into the new one with an E.M.F. which increases with the current, and hence the rate of rise is greater, the larger the current. In Fig. 24 this effect is small, but in Fig. 26 it is the principal factor, and the rate of rise differs markedly for the three currents.

Examining the next parts, it is notable that the current has not only reached its maximum before the full contact, but has even begun to fall either before or soon after full contact is attained. On light load there is an excess of reversing E.M.F., which causes a reverse or circulating current, large in 24 and small in 26. In the former it is

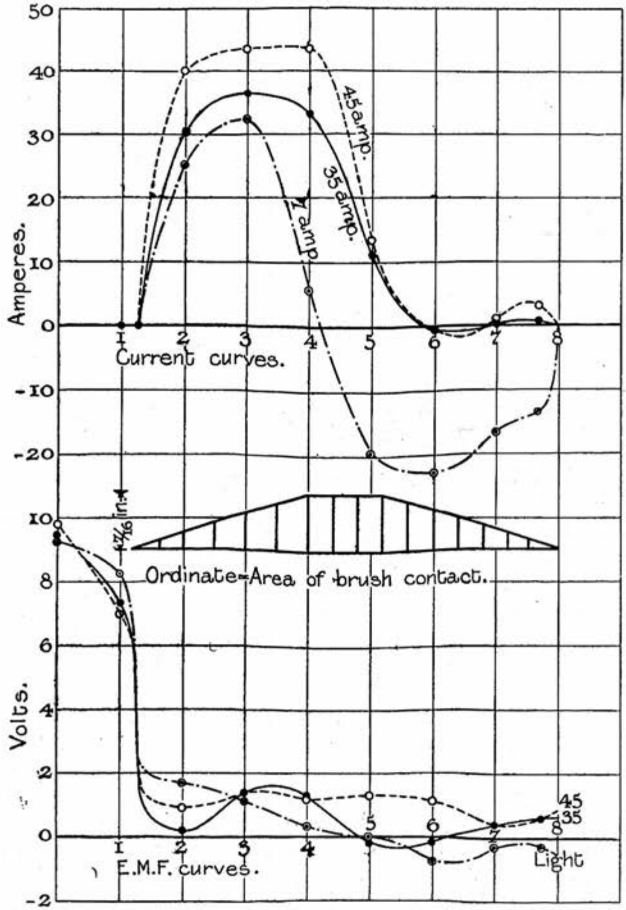

FIG. 24.—Current and E.M.F. in Segment, Brush behind Centre.

dying away slowly, as the coil moves out of the field, when the diminishing brush area cuts it off abruptly, with a corresponding rise in the E.M.F. curve. With 35 and 45 amperes the current does not rise again to any appreciable extent, and commutation is evidently perfect. Owing to the distortion of the field by the larger currents, there is a slight reversal of the field, causing the current to start in the wrong direction, until cut off by the brush resistance. The phenomena in Fig. 25 are very similar on a reduced scale. In fact, up to half load this central position of the brushes is better than the previous one. Probably an intermediate point between 7 and 8 would show the half-load current rising again, as indicated by the E.M.F.

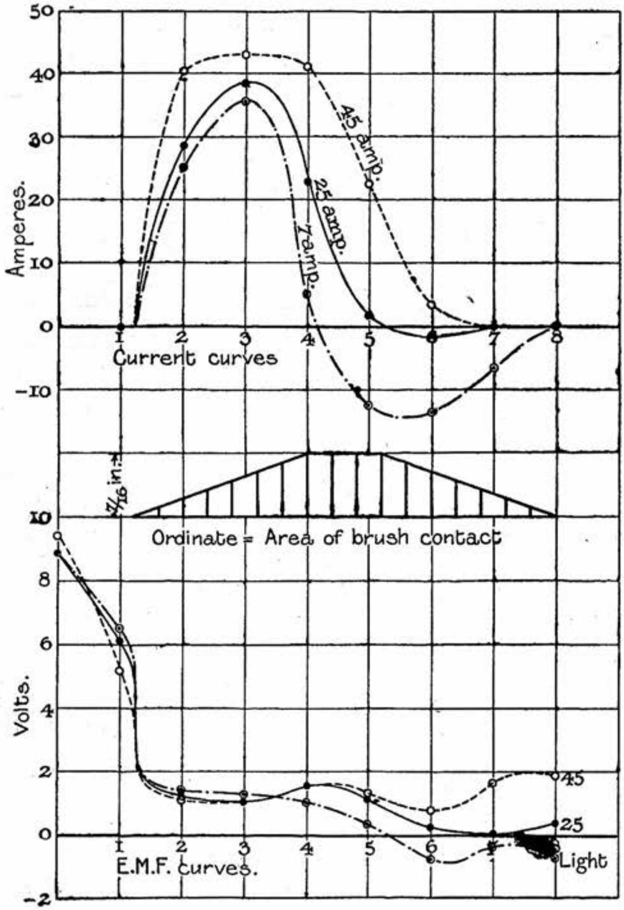

FIG. 25.—Current and E.M.F. in Segment, Brush in Neutral Position.

Fig. 26 shows the effect of insufficient reversing E.M.F. at first, which does not matter, and of the wrong E.M.F. at the end, which is more important. Without this E.M.F. the current of even 45 amperes would evidently have risen and died down by the action of the brush resistance alone, finishing easily by the end of the contact. It may be of interest to say that, taking t as the half-time of contact, and R as the resistance of coil, lug, resistance, and brush contact (at the full), the product Rt is twice the inductance of the coil, a condition which on some theories of commutation should insure satisfactory results. In the present instance the E.M.F. from the fringe of the approaching

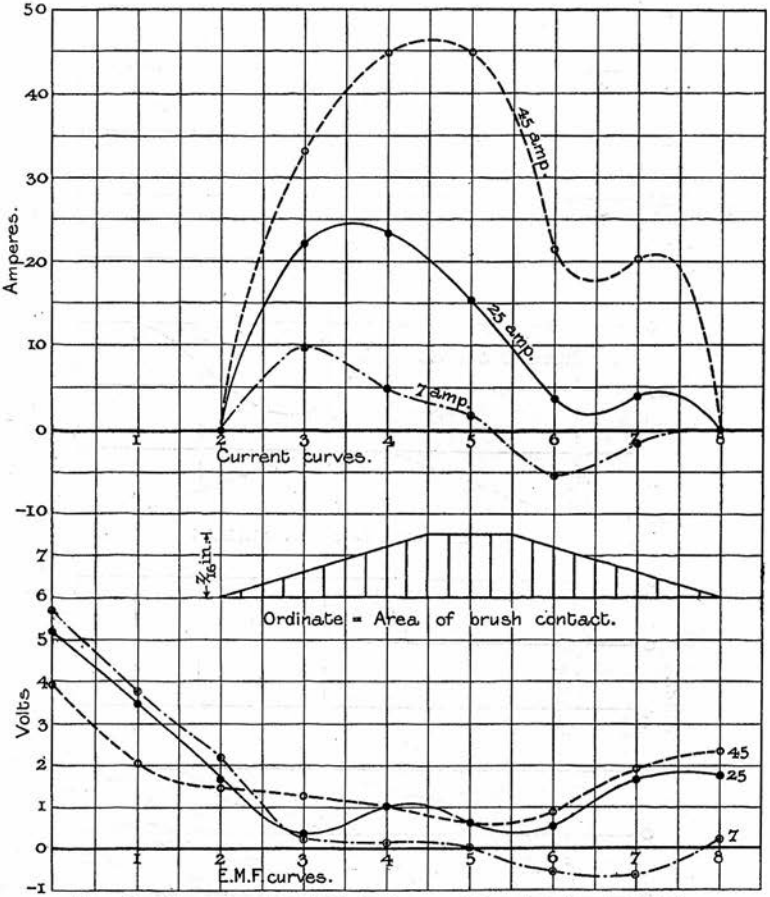

FIG. 26.—Current and E.M.F. in Segment, Brush in front of Centre.

pole keeps up the current, which is abruptly brought to zero by the increasing brush resistance, the E.M.F. rising to correspond.

The E.M.F. curves during contact show that this varies between 0·5 and 1·5 volts, which may be taken as about 1 volt. The current density is about 90 amperes per square inch with the 45-ampere curves when there is full or nearly full contact, rising to 150 amperes in the earlier parts of the curve. This corresponds fairly well with the values given in Part I., for the brushes resembled the S quality, and this value is for one brush only. The current density at the leading edge is very high, falling rapidly until at the trailing edge it is in many cases zero or in the reverse direction. But over the first third of the brush, where most of it gets through, the density is fairly uniform. This is of some importance, for Professor Arnold (*loc. cit.*) has shown that when the current varies with great rapidity the ratio of instantaneous E.M.F. to current is nearly constant, and he applies this to the case of a dynamo brush. Whatever the value of the resistance may be under these conditions, it does not apply quite so strictly to the case of a brush as he assumes. Even at the trailing edge with a reversed current, the value will not fluctuate very much, unless the brush is even narrower than the one used here.

It will be noted that the current density under the brush is little affected by the circumferential size of the brush. The whole line current passes through the leading segment, even though the larger portion of the brush is touching the segment behind. We may recall the statement made in Part I., that excessive brush area serves no useful purpose, and we see that the case is really stronger against low current density than appeared before. For the anticipated decrease in the E.M.F. will not be obtained, while the idle part of the brush is at best wasting power in friction, and may also be the seat of heavy circulating currents. This machine, for example, in these tests is taking half load with one-ninth of the brush surface supplied by the makers, and we have taken it up to two-thirds of full load with a single brush of one-eighteenth of the full brush area in a special brush holder, with no sparking and with a pressure of 30 oz. per square inch. The current density must have been very great, and possibly this extreme reduction of brush area was not economical, but it is instanced to show that high current density alone will not cause sparking. In fact, it will tend to increase the brush resistance effect in forced commutation at the trailing edge, and to lower the sparking E.M.F. The only risk lies in overheating, if sparking should occur, for it will be concentrated over a shorter line with less cooling surface.

The curves of current were obtained with very steady readings, though successive tests showed some irregularity of outline. But in spite of probable changes during a single set of readings, the mean value of a succession of waves gives a height closely equal to the line current. The curves of E.M.F. were not so reliable, and it is extremely probable that the contact resistance at any one point under the brush will fluctuate, causing a corresponding fluctuation in the E.M.F. There are scarcely enough points for accurate plotting of the bends, but an increase in their number would have protracted the duration of an experiment, and would have increased the probability of change of conditions. There is a certain uniformity in the undulations which tends to show they are not simple irregularities, but an analysis of the current density and E.M.F. at each point would not be safe.

While the results of these last tests do not bring out any new phenomenon which has not been, or could not be, conjectured beforehand, they emphasise the fact that the leading edge of the brush is really the important part from the current-carrying point of view, and that the trailing edge should be reduced to its narrowest limits. The leading half should be of the best and most heavily graphitised carbon, and possibly the metallic impregnations sometimes used would be still better. But the trailing half should have a much higher resistance, preferably obeying Ohm's law as nearly as possible. The old carbon-fronted gauze brushes carry out this idea, but a single composite brush of uniform wearing qualities throughout will be more easily applied, and will require less attention. There is no need for several laminations, for these circulating currents cannot get through the leading part of the brush, and low resistance laminations at the trailing half will be harmful. The high resistance at the trailing edge will force the current to the new segment in front, which is all that is required.

The second point to which attention may be drawn is that the brush has far more power to commutate the current than is usually believed, at least by writers on dynamos. A low inductance is necessary, but a uniform high contact resistance is not advantageous, for while it hastens the fall of current in the trailing segment it also checks the rise in the new one. A reversing E.M.F. is desirable, but not necessary, as is shown by Fig. 26, where commutation takes place without its aid, and it must be noted that, while the machine is only on half load, yet it is working with only one brush arm, and all three coils are commutated at once. The conclusions drawn from the curves of sparking E.M.F. are therefore substantiated, that the less stray field there is the more safely the machine will commutate. So long as the armature field is kept away from the short-circuited coil, the strength of the main field may be reduced to any limits. If the armature coils have reasonably small inductance, then a wide interpolar space, a narrow air-gap, good brush holders and brushes not too broad, will hardly fail to produce sparkless commutation and a cool commutator.

In conclusion, we wish to express our thanks to Mr. W. G. Griffith and to Mr. H. J. Ireland for their assistance in the work on the resistance of brushes, and to acknowledge our gratitude to the Carnegie Trust for a grant in aid of this research. Their bestowal of a research scholarship has given leisure to one of us for the somewhat laborious experimental work which has been entailed, and the machines used in the tests form part of the new equipment of the electrical engineering laboratory in the Heriot-Watt College, to the purchase of which they subscribed a generous portion.

Discussion.

Mr. Mavor

Mr. H. A. Mavor: This investigation on commutation has been much required. We have here not only a very careful scientific investigation of the subject, but we are presented with valuable practical results in the form of definite advice. I think I may say from practical experience that Professor Baily's conclusions are not only fully justified by the experiments which he has carried out, but that the hypotheses which he has laid down are quite as fully established by experience in the use of machines. It has long been evident to most of us that the empirical calculations of reactance voltage and other things have only an indirect bearing on commutation. While it is quite true that we can calculate and establish by experimental results the fact that a high reactance voltage is exceedingly unfavourable to commutation, it is also true that we may design our machines with everything that can be desired in the way of satisfactory calculations as to the reactance voltage and yet find a machine which is quite unworkable. This point is clearly brought out by the fact that most designers have different limits for the reactance voltage for small machines and large ones. Professor Baily has come to the conclusion that while we must always, as it were, keep the question of reactive voltage at the top of our heads, what we want to keep at our finger-tips is knowledge of the effects of the very things to which he has been directing our attention. One of the most important of these is vibration of the brush on the commutator. This vibration may arise from many causes, from the commutator being out of truth, rough, or made of unsuitable metal. I have recently come to this conclusion from the fact that there is now a general superstition against making commutators of any cast metal because of the risk of impurities rendering the friction inconstant and uncertain. I do not think that friction in itself is a very serious matter. It produces vibration and brings about very uncertain results. Having obtained a commutator made of a homogeneous metal whose properties are known and which can therefore be dealt with by means of a suitable brush, we are again face to face with the condition of the surface of that material, and we are quite aware now that a hard-drawn pure copper commutator with a suitable surface may become very troublesome in presence of certain matters which may accumulate whether it is running or at rest. For example, the dust of textile fabrics is most injurious to the running of the commutator. In that connection the well-known empiric use of paraffin wax and such matters referred to by Professor Baily is interesting as giving an indication that lubrication is very important. After having considered the question of brush resistance, lubrication, and other matters, I must confess to a hankering desire to go back from the carbon brush to the copper brush. We know how, with some well designed old machines with copper brushes, the loss is minimised by the use of the copper brush, and how it is possible to get effective lubrication on the commutator by the mere accidental leakage of oil on it which occurs on all old machines. We can see machines that have been in use for twenty years with copper brushes, changing loads, and all the vicissitudes they have come through, with the commutator in perfect condition. There does not seem, after all, to be any essential reason why we should incur the loss by the use of a carbon brush at all. Mr. Mavor.

Mr. W. B. SAYERS: I am much interested to hear that Mr. Mavor is again thinking of copper brushes. I have had the experience of Mr. Sayers.

Mr. Sayers. seeing my experiments to a large extent extinguished by the advent of the carbon brush. I had been experimenting at Messrs. Mavor & Coulson's works with a view to obtaining sparkless commutation with fixed brushes by means of various devices, and I had attained a certain amount of success in that direction when the carbon brush came into the field and seemed to do very easily what I had found a troublesome and difficult thing. However, it has long since become clear that the carbon brush is not the complete solution of the matter which it was said at first to be, inasmuch as we see now many kinds of commutating poles and similar devices being introduced which were said by many at the time to be quite unnecessary. The carbon brush is said to do all that is required.

Mr. Nicholson. Mr. J. S. NICHOLSON: The paper would have been more interesting and instructive, especially to those who have had an opportunity of carrying out similar experiments, if diagrams of connections and apparatus had also been given. In the experimental determination of the brush contact resistance the fall of potential is measured across both brushes. The experiment would probably have been more complete if, in addition, the fall of potential between each brush and the copper drum had also been measured. That has already been done in previous researches, and I understand that the fall of potential is different at the two brushes.

Mr. Robinson. Mr. E. LEWIS ROBINSON: As regards Mr. Nicholson's remarks about the difference in the volts lost between the commutator and the positive and negative brushes respectively, experiments have been carried out, and it can generally be taken that the drop is twice as large at the negative compared with that at the positive brush. This can be measured by using an ordinary brush insulated from the holder and pressed on to the commutator so that it carries no current. By connecting this brush and the arm to a voltmeter, the lost volts can be measured. With regard to paraffin wax, care should be taken in using this on commutators. If the commutator is hot the wax immediately disappears; again, if the commutator is at a temperature lower than the melting-point of the wax, the commutator becomes sticky, the contact resistance goes up, the brushes chatter, and sparking results.

Mr. Kelsall. Mr. A. H. KELSALL: With regard to the last curves showing the rapidity with which the current is transferred from the "leaving" commutator segment to the "making" commutator segment, I have been wondering whether Professor Baily eliminated the possibility of error due to microscopic differences in the level of the bars, seeing that he was working with only three bars fitted with resistances and taking his readings on the centre one. Differences of level must enter enormously into the question, and Professor Baily has already obtained some results showing a tendency to vibrate. I suppose I am right in concluding that Professor Baily is distinctly in favour of high densities, and I am wondering whether there is any special reason why he did not go beyond the 60 amperes in his density experiments. I would have liked to have seen the curves traced out for higher densities. In the case of the curves where the pressure seems to be ample for vibration, the curve is still dropping rapidly at 60 amperes. With regard to Professor Baily's figures for friction for different makes of brushes and holders, it would be interesting to know whether these are all of the type known as the box-type holder, or whether any of them are of the hammer type. I think Professor Baily, a couple of years ago, expressed a preference for the hammer type, and I should be interested to know whether these recent experiments have modified his opinion on that point or not. For instance, the pressure on these brushes, from which the coefficient of friction was determined, is, I suppose, the measured pressure due to the spring, but in hammer-type brushes the friction itself has a tendency to increase or reduce the actual pressure between the brush and the commutator, according to the direction of rotation, and whether the tangent passes between the fulcrum and the commutator or outside the fulcrum. In some types of brushes I believe that this augmentation or reduction of the actual pressure is quite an important feature. I think also that there is some question as to the distribution of pressure over the surface of the brush, so that a tangent at the centre of the arc of contact may not be the mean effective tangent. Mr. Kelsall.

Dr. J. T. BOTTOMLEY (*communicated*): The first subject dealt with in the paper is contact resistance and the effect of lubrication. This is a most interesting inquiry, but I wish that the experiments had been more judiciously planned out, so as to obtain the maximum of information, and guidance towards some sort of laws, if these are to be found. The pressures, which, by the way, are measured in a quite unrecognised unit, in ounces (what sort of ounce is not stated), are said to range from 7 oz. to 46 oz., but the numbers chosen were 7, 12, 18, and 46. I can think of no relation between these numbers, and if we look at the curves, they are spaced so irregularly, and in a manner so peculiar, that one can scarcely help thinking that there must be some factor concerned in the result which has not been taken into account. Let us compare, for instance, the speeds 1,430 and 3,300 feet per minute, and note the rise in pressure from 46 oz. to 24 oz. at the two speeds and that from 18 to 7, at 1,430, and 18 to 12, and 12 to 7 oz., at 3,300 feet per minute. Further, the speeds chosen for experimenting have no simple relation with each other. It seems to me that it would have been much more instructive had the pressures and speeds been raised, in the successive experiments, either by successive equal increments or else by successive doublings. In spite of the difficulties thus introduced, and in spite of the great difficulties of the inquiry, the authors have obtained results which are wonderfully concordant. The gist of these is given in Table I., and in an empirical formula connecting electromotive force, current, and pressure. It is here that the inconvenience of having the pressure expressed in ounces presents itself in an unfortunate way. The results obtained with lubricated brushes are highly interesting. It is not, perhaps, quite generally known that even in the case of the plugs of a resistance box the Dr. Bottomley.

Dr. Bottomley.

resistance at the plugs is markedly reduced if the plugs are thinly smeared with light paraffin oil. I believe this was first pointed out by the President of the Institution, Dr. Glazebrook, who found this to be the case in the course of his work at Cambridge and at the National Physical Laboratory. Probably the paraffin helps to clear away the film of air which invariably covers the brass surfaces, no matter what trouble is taken, by pressing the plugs into the holes, to get rid of it. The film of paraffin is more easily pressed aside from between the brass surfaces which come in contact than the corresponding film of air. In any case, the result is certain, a fact which I have verified. At the same time I must say that my experience is altogether against lubricated brushes. The copper, or other metal, of the commutator segments does not and cannot wear down at exactly the same rate as the mica which insulates the segments, and the mica gets wetted by the lubricant. The particles of metal or carbon from the brushes tend to stick to the mica, instead of being blown away, as is the case when the surface of the commutator is quite dry, and a tendency to spark is the invariable result. The results of the authors with regard to commutating poles seem to me to be of considerable value. It is to be hoped that they will be able to push this work further, and with the assistance of other types of machine. Sufficient experimenting has not, up to the present, been carried out to warrant safe generalisation.

Professor Baily.

Professor BAILY (*in reply*): It has been pointed out by Mr. Mavor that a large machine can be made to commutate smoothly under a higher reactance voltage than would be safe with a small one, and possibly the reason may be obtained in our paper. For while the air-gap and the magnetomotive force in it are not much greater than in the small machine, the linear interpolar distance is considerably larger, and hence the stray field at the coils under the brushes is smaller. Therefore, when running with fixed brushes the sparking E.M.F. does not rise above a moderate value, and the brush resistance alone is capable of checking the current, even against a high reactance. Considerably smaller air-gaps, similar to those of induction motors, might be used with advantage, and with no increase in exciting current a pole shoe of less breadth would then be possible. At the same time sparking is a phenomenon not always easy to explain, nor is it due to a single cause. As an instance a particular motor was made with a commutator of cast copper, which on test ran without any sparking. But after a continuous run of some twenty-four hours it would begin to spark violently. The commutator was changed and the trouble disappeared. Some small difference in the surface may be the only variant between a good machine and an obviously bad one.

Mr. Mavor has a tenderness toward the old copper brush, and, indeed, for low electromotive forces the losses in carbon brushes may rise to extravagant values for resistance and friction. But for anything like 400 or 500 volts the loss is not important, and the advantages are great. It must be remembered that not only is the reactance of a coil in a slot high, but in cases where there are more commutator segments than slots, two or more adjacent coils lie in the same slot, and it is not possible to give a correct position to the brushes such as would be required on the ordinary theory of current reversal by an induced E.M.F. Hence there must be a good deal of forcing, or trust in brush resistance, however carefully the brushes are adjusted, and the gauze brush will not be working under the conditions possible in smooth-cored machines. Even with commutating poles a very nice adjustment of field will be necessary. For example, in our tests on the 15-H.P. motor, we found that the three coils in one slot produced markedly different sparking E.M.F., and the increase in circulating currents and sparking was alarming when gauze brushes were used. It is possible to use fixed gauze brushes under suitable conditions, for the motors made in 1891 for the City and South London Railway locomotives ran with fixed central brushes under a speed variation of 2·5 to 1 with full load and practically no sparking. But the speed was low and the field magnets very powerful, so that the distortion was small, while the armatures had smooth cores and only one turn per segment. The E.M.F. set up in the coil would be very small, and with so small an inductance the current would be broken quietly. But they were not cheap machines. Professor Baily.

The question has been raised whether there is a difference between the drop of potential at the positive and that at the negative brush. Beyond noting that there is a difference, we did not pursue the subject, for the difference appeared to be probably due to thermo-electric forces between the surfaces of copper and carbon, and as the temperature of the carbon surface was likely to be variable, it was considered preferable to eliminate the effect by reading across both brushes. Professor Arnold, *loc. cit.*, has examined this matter more fully. The method of testing this and the drop of E.M.F. generally, which was proposed in the discussion, viz., to fit an insulated brush by the side of a working brush, with a voltmeter between, does not yield very definite information when used on a commutator, for as the current density in each part of the brush varies at different times when a segment passes under, the resulting E.M.F. refers only to an average value of the current. But it is a useful practical test. We tried taking readings between the brush and a point contact pressed against the commutator, placing it at the centre and near the two edges of the brush. But the values, though quite definite and regular, had no very definite meaning, since they afforded only an average over the whole segment breadth, and we accordingly arranged the more troublesome contact-maker method.

Some surprise has been expressed at the very trifling amount of increase of E.M.F. produced by a lubricant, and we certainly anticipated quite different results. Without proper care, however, a lubricant may cause a good deal of trouble, and its use is more adapted to central station dynamos than to small motors which receive little attention. I am informed that carbon brushes boiled in paraffin give good results, but I have not tried them.

In reply to Mr. Kelsall's question, we did not experiment on more

Professor Baily.

than one segment. The surface of the commutator was quite smooth, and we had no reason to suspect any irregularity. If there had been any depression or undue elevation of the segment in question, the effects would have destroyed all hope of consistency in our readings. It would have been impossible to put resistances in all the lugs, because there was not room for them; but it would have made no difference to the current values in the segments under the brush at the instant of taking a reading. All of these lugs had resistances, and the reading ceased until they came round again.

We have been criticised for limiting the current density to 60 amperes per square inch in the first part of the paper, and certainly, if the last part had been done first, we should have carried the values higher. At the time I thought 60 amperes a liberal allowance, and was pleased to find it a safe value. But in reality the current density was much higher on occasions, for the bedding of the brush was not always perfect. In the tests on S carbons, undertaken quite recently, the densities were increased, and no change of behaviour could be detected. The brush holders were chosen in order to eliminate vibration as much as possible, for vibration, although a very usual concomitant, is too variable to yield comparative and consistent results. The plain butt brush represents also a large class of commercial patterns, though I believe it to be inferior to the hammer type, in that the latter preserves a much superior bedding. The butt brush had for our purpose the additional advantage that the pressure was definite, and was not influenced by any frictional tangential force, whereas with hammer or arm holders there is usually a component tending to modify the pressure unless the brush arm is exactly at the correct angle.

Dr. Bottomley asks upon what principle the increase of speed values was chosen. In the tests with butt brushes, Fig. 1, he will find that each successive speed is about 50 per cent. greater than the preceding. In Fig. 5 a very low speed was substituted at the beginning to make sure of freedom from vibration, and the speed was then increased until some effect was noticed, subsequent increase being rather less than 50 per cent. each time. But in choice of both speeds and pressures we endeavoured to make such increase as would bring about a readable, but not too great change in the function sought. In Fig. 1 he has not taken the meaning of the sets of curves. The spacing increases in each successive set, owing to the increase of speed, and as the brush pressure rises, the influence of vibration comes into play only at higher speeds. Our unit of pressure was the ounce *avoirdupois.*

No examples of the Morganite brush were examined. The manufacturers have made similar tests themselves, as they have informed me since the reading of this paper, the results of which are in general agreement with ours. There is undoubtedly much to be done in the comparison of different brushes, particularly under working conditions, *i.e.*, commutating a current; but the invesitgation will be extremely laborious, for the difficulty of obtaining

Professor Baily.

consistent results and satisfactory bedding is extraordinary. If I am able to extend these experiments I shall adopt some form of hammer brush, and shall use small areas of contact to hasten the wearing-down process and to retain it when obtained. It may be pointed out now, however, that the specific resistance of a brush, so far as we have gone, seems to exert small influence on the contact resistance. Thus the specific resistances of Morganite brushes, Le Carbone X, and Le Carbone S, are roughly in the ratio 1, 3, 9, while their contact E.M.F.'s at 60 amperes per square inch are about 1·2, 1·4, 1·6, and even this difference is partly accounted for by the resistance of the short length of carbon between the surface and the potential contact. This is suggestive, but requires more examination before any conclusion can be drawn. I am inclined to believe that the mechanical qualities of a brush, such as a low friction coefficient and freedom from chattering, are more important than its resistance, as brushes are made at present. And more important than the brush is the brush holder; but this we have advocated at ample length in the paper itself.

We wish to express our appreciation of the interest which the section has displayed in the subject, and in closing we have pleasure in referring to the benefit to science that is conferred by the Carnegie Trust through their research studentships and scholarships, and to express a hope that a not inconsiderable portion of these will be devoted to researches in the problems of applied science. Those who are occupied in teaching a subject which is perpetually changing, and who desire not only to keep abreast of its scientific developments, but also to keep in touch with its commercial applications, can find little leisure for continuous experimental work, and to such an one the co-operation of one who can devote the whole of his time to a piece of work is invaluable.

Institution of Electrical Engineers.

GLASGOW LOCAL SECTION.

SOME PHENOMENA OF COMMUTATION.

By Professor F. G. BAILY, M.A., F.R.S.E., and Mr. W. S. H. CLEGHORNE, B.Sc., Carnegie Research Student.

(*Paper to be read at Meeting of Section, November* 13, 1906.)

In this paper will be described some experiments on the phenomena occurring in the process of the commutation of armature currents in direct-current dynamos and motors. It is a subject upon which much has been written, and already much experimental work has been carried out. With the theoretical writings the authors do not propose to deal, beyond an occasional reference where the experimental results corroborate or correct the assumptions of the writers. Some of the experimental work to be described is substantially a repetition of earlier work, but amplified to more exact determinations, or carried out in a different manner. The authors trust to be excused if they fail to make appropriate reference to the many papers which have been published in many languages.

The paper deals with the contact resistance of the brush, the value of the brush current, the currents in the short-circuited coils, and the electromotive force between the segment and the trailing edge of the brush. We shall begin with the question of the resistance of the brush contact.

In equations connecting the currents and E.M.F.'s under the brushes in direct-current machines it is frequently assumed that the resistance of the brush contact and brush is a constant, although it has been shown by Mr. A. H. Moore, Dr. E. Arnold, Mr. E. B. Raymond, and probably others, that this is by no means the case. Current density, speed, and pressure all exert an influence on the resistance, and the experiments to be described are a more exhaustive repetition of the work above mentioned. There were some discrepancies to be noticed in their results, and the precise effects of speed and pressure had not been examined closely, so that a full investigation appeared desirable. The influence of the character of the brush holder and the effect of lubricants were also points to be elucidated.

The mode of experiment was of the simplest character. A cast-iron pulley was covered with a heavy band of copper, turned and polished to a true surface with a diameter of 11 ins. This was mounted on the spindle of an electric motor. The two carbon brushes were set on the horizontal diameter, and current from a battery was passed through a variable resistance and an ammeter and across the pulley from brush to brush. The drop in E.M.F. across the two brushes was read on a voltmeter by potential leads soldered to the brushes themselves, so that thermo-electric effects were eliminated, and no brush-holder resistance was included. The resistance of the copper drum was negligible, but the resistance of some ½-inch length of carbon on each brush was included, as representing probable working conditions, and this has not been subtracted in the following readings. It amounts to 0·04 volts on the two brushes with a current of 60 amperes per square inch.

The carbons were supplied by Le Carbone Co., the best quality, called X, being used. It was a very dense graphitised carbon with a specific resistance of 0·00193 ohms, or about 1,200 times the resistance of copper. Common grades of brush carbon have usually about three times this resistance. It was by no means a soft carbon, wore slowly, and took a high polish.

Preliminary experiments showed that vibration would play an important part in the resistance, and in order to simplify the first tests, brush holders were used in which vibration would be as small as possible. A rigid frame was fixed to the bed-plate, and the carbons were soldered into short brass tubes, sliding in other tubes fixed to the frame, and being pressed on to the drum by helical springs. The inertia was therefore little more than that of the carbon blocks themselves, while sideways vibration was prevented by the close fit of the tubes. As the wear during the tests was small, only a quarter inch of carbon projected from the tube, and the guide-tube extended almost to this point. The area was 1 sq. in. in all tests, the same pair of carbons being used all through.

I.—Determination of Contact Resistance of Dry Carbons and Copper.

The first experiments were devoted to the conditions of dry (*i.e.*, unlubricated) contact. The surface was kept perfectly clean by a polishing pad continuously pressing on the drum. There was an indication that a slight coating of carbon dust was beneficial, causing a slight diminution in both fall of potential and friction. But as the clean surface was more definite this was preferred, and the effect of the carbon lubricant was too small to modify the results appreciably.

Readings were taken at speeds from 860 up to 3,300 ft. per minute and with pressures ranging from 7 to 46 oz. per square inch. It would cumber the paper to quote all the numerical results in full, and in general these will be embodied simply in curves giving the mean values of several sets of readings under the same conditions. Fig. 1 shows the relationships obtained. There are some irregularities which refused to be eliminated, but the general trend is unmistakable. Down to 18 oz. pressure the speed does not influence the result. With 12 oz. the effect is barely noticeable at 2,300 ft. per min., but is marked at 3,300. With 7 oz. the effect is seen at 2,300 ft. per min., but not at 1,430 ft. It is clear that the influence of speed is indirect, causing vibration, which reduces the efficiency of contact. This will be seen more clearly below, when vibration is purposely introduced.

Fig. 2 gives the mean values of these, eliminating curves affected by

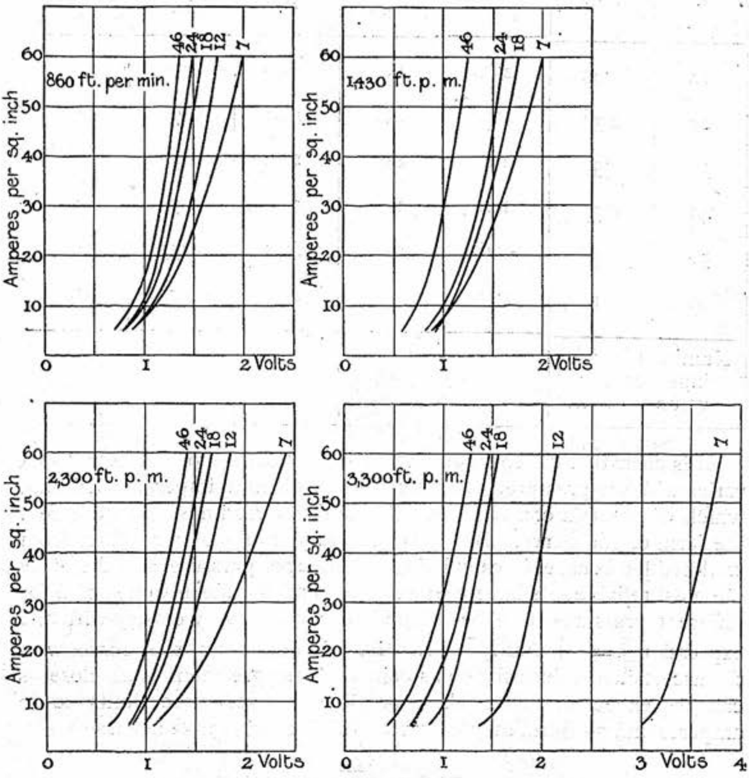

Fig. 1.—Effect of Pressure and Speed on Contact Resistances.

speed. Representing the mean of a large number of readings, it may be taken to portray the relation of E.M.F. and current for different pressures, when vibration is absent.

The curve may be expressed by the function $kE = i^{0.28}$. Assuming this index, and calculating the value of k for each point from 10 amperes to 60 at each pressure, the value of k given in Table I. is seen to be fairly constant for each pressure, and, except in the case of 7 oz., the irregularities show no regularity, so that this function expresses the ratio of E.M.F. to current with considerable accuracy, assuming that there is no vibration. Each vertical column is derived from the mean values of a number of sets of readings, the numbers being given in the last line.

TABLE I.—VALUE OF RATIO $i^{0 \cdot 28}/E$.

i.	$i^{0 \cdot 28}$.	Pressure in oz. per sq. in.				
		46.	24.	18.	12.	7.
10	1·90	2·26	2·02	1·90	1·70	1·75
20	2·30	2·28	2·04	1·93	1·70	1·69
30	2·57	2·25	2·06	1·96	1·70	1·65
40	2·79	2·28	2·04	2·00	1·73	1·60
50	2·98	2·28	1·98	2·00	1·75	1·59
60	3·10	2·22	1·99	1·99	1·73	1·55
Number of readings for each value ...		11	16	10	7	4

It is clear that the constant only, and not the form of the expression, varies with the pressure. Therefore any accidental imperfect bedding, which will remain constant through one set of readings, will not affect the form of the curve. But it is necessary to use only readings from well-bedded brushes in calculating the effect of pressure, and therefore the most reliable sets have been selected, and the mean values of k for different pressures have been found to conform very closely with the expression $k = 1 + 0 \cdot 22 \sqrt{P}$. In Fig. 6 is delineated this curve, with the ascertained values shown as points. The agreement is as close as can be expected. The full expression, between the limits 10–60 amperes and 7–46 oz., may be written with considerable accuracy—

$$E = \frac{i^{0 \cdot 28}}{1 + 0 \cdot 22 \sqrt{P}}$$

to represent the relation of E.M.F., current, and pressure with a well-bedded brush free from vibration.

Doubt may arise whether a plain copper drum really represents a commutator. Assuming that the surface of the commutator is smooth, there seems no reason to doubt this. In confirmation it may be mentioned that these results agree fairly closely with those given by Dr. Arnold, who used a commutator for his tests, and some further tests will be given in this paper, in which the readings of E.M.F.

and current across the brush contact of an actual motor in operation were obtained, which are also in close agreement. But the later experiments will show that, as the distribution of current is by no means uniform, the current density may be much higher than the value obtained by dividing the total current by the brush area, and this equation can be taken only as a first step in the solution. It applies, however, rigorously to the case of collecting rings in alternators and induction motors.

It will be well known to all that the actual surface of contact is often only a small proportion of the total brush surface, and it is interesting to examine what effect will be produced by imperfect bedding. Let the area be reduced to $1/n$ of its nominal value. Then

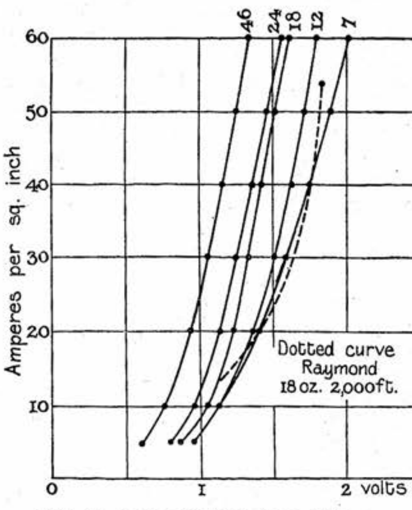

FIG. 2.—Mean Values from Fig. 1.

the pressure per unit area and the current density are increased n times. The E.M.F. is changed to the value—

$$E\frac{i_n^{0.28}}{i^{0.28}}\,\frac{1+0.22\sqrt{P}}{1+0.22\sqrt{P_n}}.$$

Within large limits this factor differs very little from unity. For example, if only one-fifth of the brush is bearing, the increase of E.M.F. is not more than 5 per cent. Hence we see, what appeared extremely improbable from the nature of each separate curve, that imperfect bedding has scarcely any influence on the brush losses. It follows also that with a given spring tension and current the loss will be much the same whatever size of brush be used within reasonable limits, and there is no advantage in using low current densities.

Moreover, a small, and consequently light, brush will vibrate much less, and will therefore be less liable to spark. The frictional losses will be also unchanged, for it will be shown later, what is indeed quite normal, that the frictional loss is proportional to the pressure. There will be a certain ratio between current density and pressure per unit area at each speed, at which losses are a minimum, the ratio being kept low at low speeds and high at high speeds. The curves in Fig. 3 show the total losses in watts per ampere collected, plotted against

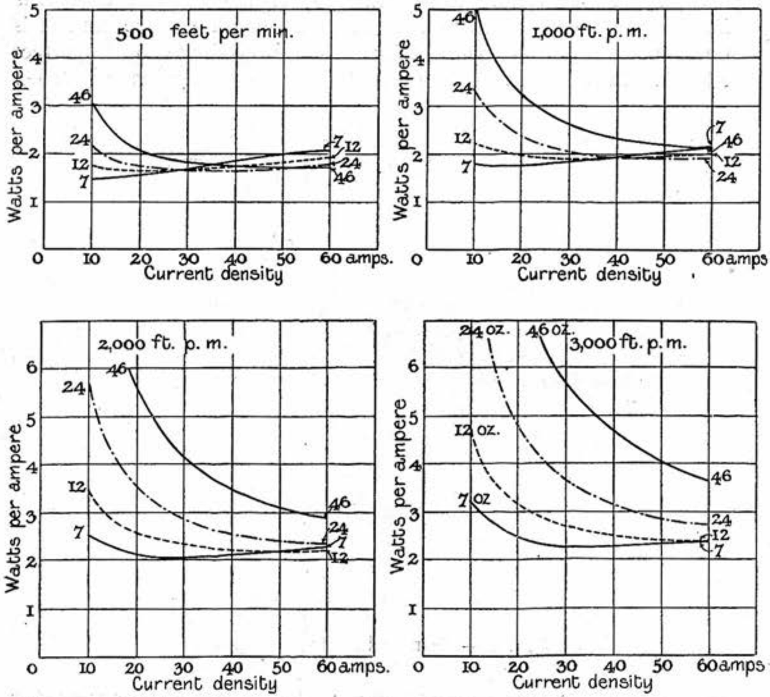

FIG. 3.—Total Losses per Ampere Collected, for various speeds, pressures, and current densities.

current density, for various pressures and speeds, the values being taken directly from the curves in Fig. 2, and the friction constant being 0·0005, for which see later. It will be found that when horizontal lines are drawn through, representing a constant loss, the ratio of current density to pressure is approximately constant. At a high speed, say, 3,000 ft. per minute, the 7 oz. pressure is the most economical with a c.d. of 30, or a ratio of 4 to 1, while at 500 ft. per minute we may use 7 oz. at 9 amperes, 18 oz. at 24 amperes, or 24 oz. at 32 amperes with nearly equal minimum loss, or a ratio of 1·3 to 1. Of course these conclusions will be modified by considerations of sparking and heating, and it may not be possible at high speeds to use the most economical ratio.

Mr. Hobart ("Electric Generators") mentions 40 amperes as a safe limit, and 20 oz. as good practice, or a ratio of 2 to 1. If the curves of total losses are examined for the point corresponding to 40 amperes and 20 oz., it will be seen that there is not much wrong with these values, except at the highest speed, and here a lighter pressure and a greater current density might produce sparking. It is, indeed, satisfactory to find that over a wide range of speed, pressure, and current density a low value of total losses can be obtained; but there is a heavy penalty if these limits are much exceeded. There is no advantage in using a low current density, and in order to obtain the best conditions over all loads of a dynamo, the current density at full load should be fairly high, a few well-designed brush holders being better than a number of cheap ones, especially at high speeds, where a low current density is extravagant.

II.—Friction of Carbon Brushes.

The friction was measured by reading the power absorbed by the driving motor when the brushes were on and off respectively, the readings being taken immediately after the E.M.F. readings at every set. For convenience, the power wasted in friction has been expressed by the formula $W = \mu\, v\, P\, A$ watts, where—

v = velocity in feet per second.
P = pressure in ounces per square inch.
A = area in square inches of both brushes.

The co-efficient μ shows some variation, but the divergencies from the mean do not point to any modification of the above formula. The value obtained with the above-described brush holders and a polished surface, as a mean of 18 readings, was $\mu = 0{\cdot}00065$. Values were also obtained when other brush holders were used, which may conveniently be given here.

Value of μ—

1. Direct-pressure brushes ... ... $= 0{\cdot}00065$
2. Padded brushes and heavy holders ... $= 0{\cdot}00050$
3. Heavy brush holders ... ... $= 0{\cdot}00037$
4. Parshall's value ... ... $= 0{\cdot}00043$
5. Raymond, graphitised brushes ... $= 0{\cdot}00070$

The agreement between Raymond's value and the first one is fairly close, and possibly his brushes were softer than ours. The value with heavy holders is low, and this is doubtless due to the vibration. An examination of Mr. Moore's experiments, from which Mr. Parshall takes the above value, shows that his brush holders probably had a good deal of vibration, and hence the frictional loss is also low. It should be added that in the case of 2 and 3 the drum was not continuously polished, and, as has previously been stated, the carbon dust acts as a lubricant to a small extent, reducing the friction. Probably the value

0·0005 will represent the usual working conditions with fairly hard brushes, although at high speeds, where some vibration is probable, it will be reduced to 0·0004.

III.—Experiments with Lubricated Brushes.

It is a common practice to use some lubricant, which generally contains hard paraffin wax as the basis. To examine what influence the lubricating film exerts on the E.M.F., a set of readings was taken with the same brushes and holders as in Series I., but lubricating the drum with paraffin wax. It was not so easy to ensure uniformity of lubrication as uniformity of cleanliness, particularly with a solid or pasty lubricant. When first put on, the lubricant causes sparking and a rise in the E.M.F., and a consistent condition is obtained only after

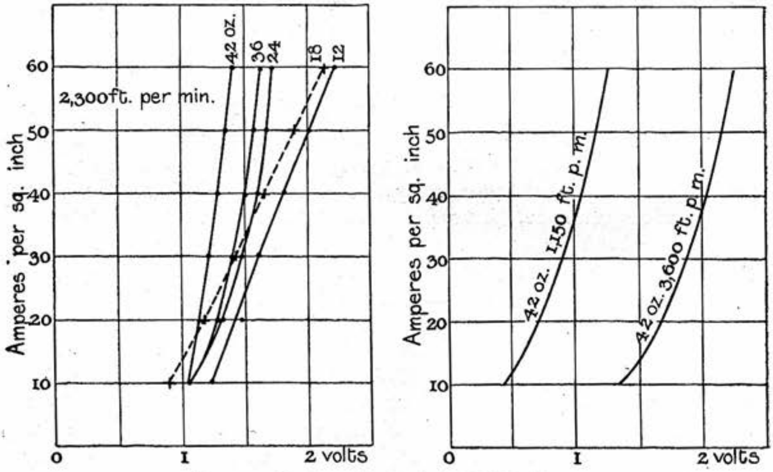

Fig. 4.—Tests with Lubricated Surface.

the wax has become softened and uniformly spread. Therefore continuous application was not possible, and some variations were inevitable in the quantity of lubricant on the surface. This made less difference to the E.M.F. than to the friction. The temperature of the surface affected the viscosity of the wax, and on a cold surface the effect was not satisfactory. This, however, is not likely to occur in practice, and in the tests the drum and brushes were warmed up by a large current before readings were taken.

Fig. 4 shows a complete series taken at 2,300 ft. per minute, and it will be seen that the lubricant has produced very little change in either the shape or the value of the curve, until the pressure is reduced to 18 oz. Below 12 oz. the readings were irregular, and the E.M.F. rose rapidly, showing that there was imperfect contact. The speed exerts considerable influence on the E.M.F. Even at a pressure of

42 oz. there is a continuous change between 1,200 ft. per minute and 3,300. At 1,200 the E.M.F. was exceptionally low, whereas at 3,300 the value is nearly doubled. With a dry surface (Fig. 1) there was no change at all.

The frictional loss was determined at the same time, the following values being obtained :—

Pressure	12	18	24	36	40	42 oz.
$\mu =$	0·00013	13	15	074	065	10

or a mean value of 0·00011 watts per oz. per foot per min. per sq. in. The values given above show rather wide divergencies, due to differences in temperature and thickness of lubricant, but in all cases the value is much lower than that found with a dry surface.

Two special commutator lubricants were also applied, one a mixture of paraffin and graphite, the other apparently consisting of powdered paraffin with a little soapstone, coloured and scented with unimportant constituents. The results were much the same as those obtained with paraffin wax alone, though it is possible that with an ungraphitised brush the addition of graphite in the lubricant may be beneficial.

Several liquid lubricators were tried, applied continuously by a pad against the drum. Among them were light engine oil, paraffin oil, and toluol. None were advantageous. The thinner lubricants somewhat increased the E.M.F. and made little difference to the friction, while the engine oil rapidly clogged and increased the E.M.F. considerably.

The results of the tests with paraffin wax are remarkable, and were certainly not expected by the authors. The curve at 1,200 ft. per minute (Fig. 4) is the mean of six sets, all agreeing closely, so that no accidental error was possible, and it will be seen that the values are as low as any obtained with the dry surface. The lubricant, although an insulator of enormous resistance, permits the passage of large currents with absolutely no interference, and yet is present in sufficient thickness to reduce the friction to one-fifth of its value for dry surfaces. This is an attractive subject for discussion, but one which cannot be entered upon here. It may be added that when the drum was stopped, the resistance was very irregular, and it generally rose to what was practically total insulation.

Whatever the explanation, there is no doubt that the action of the lubricant is beneficial in reducing friction and wear and tear of brushes, without any counterbalancing increase in electrical losses, provided a little attention is bestowed on it. On account of the reduction in friction losses the pressure may be increased to some 30 or 40 oz., and over a large range of current density current can be collected at a total loss of less than 2 watts per ampere. The data are scarcely adequate for precise calculations, and we shall not attempt any formula connecting E.M.F., current, speed, and pressure, which would doubtless be much affected by the degree of lubrication ; but the general character of the phenomena and their practical application are sufficiently clear.

IV.—Effect of Vibration.

The influence of vibration has already been noticed at high speeds. To examine this further, brush holders were made in which there was a considerable tendency to vibration—long arms pivoted at one end and possessing more inertia. The same brushes were used. There is no need to enter into details, as the tests only show what to avoid.

Fig. 5 shows the results. At 580 ft. per minute there was no vibration, and the values of E.M.F., even down to 12 oz., correspond closely with the previous values. At 1,600 ft. the effect is marked, at 2,300 still more marked, the increase showing at a pressure of 55 oz., while at 3,200 ft. the E.M.F. runs up to nearly 9 volts. Although the collection at this speed was not sparkless, it would scarcely have been deemed very bad on a dynamo. At these high speeds the collection is clearly almost entirely through the arc, as the E.M.F. is almost constant between 10 amperes and 40, and it is remarkable that the readings were exceedingly consistent, repeated sets not varying more than some 3 per cent.

The vibration was reduced by inserting pads behind the carbons, and a marked improvement was noticed. At 1,430 ft. per minute the E.M.F. was still normal, at 2,300 ft. it was normal down to 16 oz., but at 3,200 ft. it was barely normal even at 42 oz. It is scarcely necessary to reproduce these curves.

It will be noted that the effect of pressure is twofold. It reduces vibration, and it improves the actual contact independently of any vibration. As has been pointed out, the efficiency of collection is improved by keeping the pressure low, especially with dry surfaces; but the reduction must stop sharply at the point where the particular brush holders in question show a tendency to vibration, or losses will run up rapidly. It is important to notice that the E.M.F. maintains a high value with small currents, so that an increase in brush area will not eliminate the loss, unless, by subdividing the brushes, a probability is obtained that some of them will be making good contact. These results strengthen the opinion expressed above, that a few well-designed holders are better than a number of bad ones.

V.—Resistance of Brushes Standing.

Though not a practical condition, it will be interesting to examine the resistance of the brush contact when standing. This was determined during some of the tests, after stopping the drum. The current was raised from 10 to 60 amperes as before, and while occasional abnormal values of E.M.F. were obtained, the readings for the most part showed that the ratio of E.M.F. to current was constant for a given pressure, and that Ohm's law holds good. The resistance diminished as the pressure increased, and the conductance may be written $\frac{i}{E} = 0{\cdot}6\,P + 24$, though no great reliability can be placed on

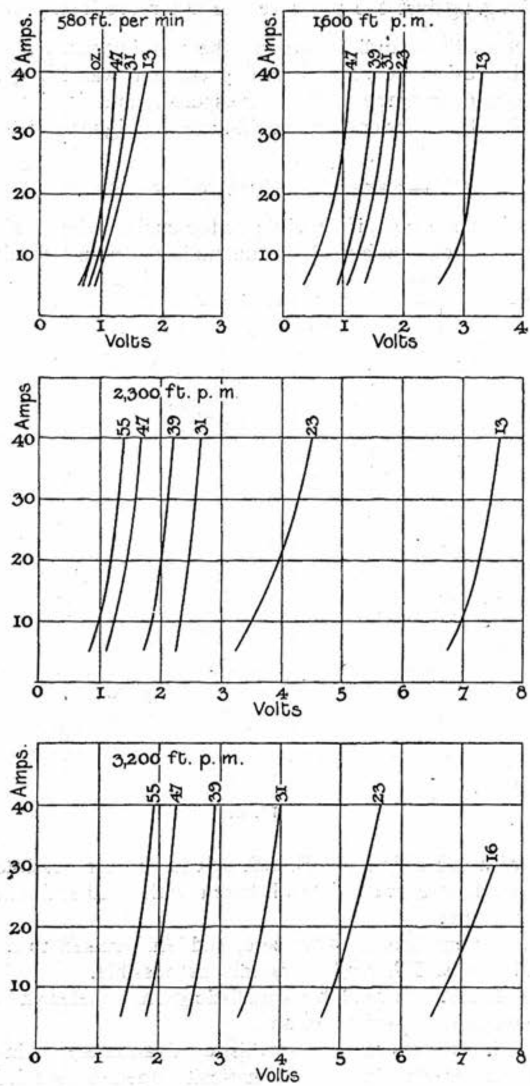

FIG. 5.—Effect of Speed and Vibration.

the formula. Fig. 6 shows the two curves of the ratio $\frac{i}{E}$ standing and $\frac{i^{0.28}}{E}$ running, against the pressure, the latter producing considerably more effect on the standing than on the running values. With small currents the resistance of the running contact was the greater; but between 60 and 70 amperes the curves cross, and for higher current densities the stationary contact would have the higher resistance.

VI.—Effect of Time on the E.M.F.

To obtain some clue, if possible, to the curious shape of the curve E/i, some variations were made in the mode of taking readings, in the

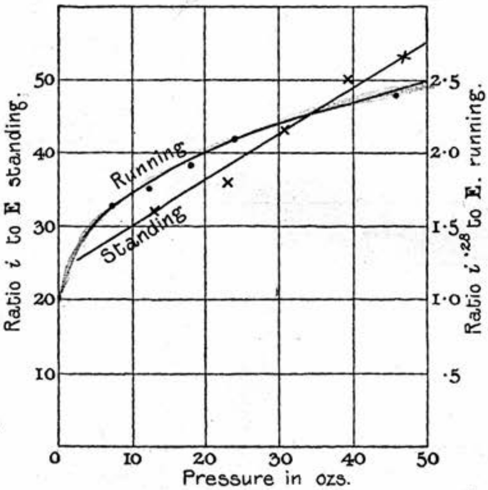

Fig. 6.

direction of ascertaining the E.M.F. at the earliest possible moment. For the previous curves were all taken with a liberal allowance of previous running.

1. The current was kept at zero, suddenly raised to a particular value, and the E.M.F. read as rapidly as possible.

2. The E.M.F. was read by a ballistic galvanometer and condenser when the current was switched on.

3. The E.M.F. was read by a ballistic galvanometer as in No. 2, but the galvanometer circuit was automatically opened a small fraction of a second after closing the main circuit, thus eliminating the effect of any subsequent change.

Readings were taken at 24 oz. pressure and 1,430 ft. per minute. To avoid cumbering this paper with too many curves, it may simply be stated that all three methods gave closely the same curve, and the mean of them all agreed almost exactly with the normal running curve at that speed and pressure. The curve of No. 3 method gave slightly lower values of E.M.F. than the others, but the difference was not sufficient to bear any deductions. It may be taken, therefore, that the E.M.F. assumes this value in an exceedingly short space of time.

The form of the curve of E/i is strongly suggestive of the shape of the curve obtained when a glow lamp is heated, but the experiment with method 3 shows that any heating must be confined to an extremely thin layer of carbon, on account of the rapidity with which it takes place. There is also the difficulty that stationary brushes do not exhibit this phenomenon, but obey Ohm's law, so that the mere fact that the contact takes place at comparatively few points, with consequent enormous current densities for a short distance, does not seem a satisfactory explanation, for some similar effect should be shown in the stationary brush. We confess our inability to suggest a theory explaining the law of variation of the contact resistance.

VII.—Determination of Sparking E.M.F.

The next part of our experiments was devoted to determining the E.M.F. between the brush and the commutator segment at the moment of separation, which we may call the sparking E.M.F., or the E.M.F. due to a sudden cessation of current in an inductive circuit, which tends to produce a spark at the point of separation. This has no connection with the reactance E.M.F. embodied in various formulæ, which deal with the value of L^{di}/dt before the break, and assume that the current has already become zero when the separation occurs. The sparking E.M.F. is therefore a measure of the failure of the machine to commutate its current in the correct manner. That this does not necessarily mean that the machine is commercially unsatisfactory is obvious from the fact that in forced commutation with fixed brushes the ideal procedure must be departed from, and we shall examine whether the conditions for reducing the inevitable sparking E.M.F. are the same as those producing an ideal commutation under the ideal conditions. We shall also examine the value of the currents circulating in the short-circuited coil, and their effect on the sparking E.M.F. and the magnetic field of the machine.

As interest is now particularly directed to the use of machines with commutating poles, this type was examined with the greatest fulness, and for comparison similar readings were obtained from a simple machine.

The machine was a 15-h.p. 4-pole enclosed motor with two-circuit wave-wound slotted armature. At 460 volts with the full exciting current it ran at 550 revolutions per minute. The armature has 1,384 bars and 173 commutator segments, with four turns per section, 29 slots with three outward and three return sections in each slot. The reactance E.M.F. calculated by Hobart's formula, if the effect of the commutating pole is neglected, is 3·5 volts. The four brush arms each carry two brushes 1 in. long and $\frac{7}{16}$ in. broad. The commutating poles had a narrow pole face $\frac{7}{8}$ in. broad, but both main and commutating poles slanted across the teeth, so that the total span was 2 ins., or nearly two slots and two teeth, as shown in Fig. 7. The makers were the Morris Hawkins Company.

The E.M.F. was measured on a high-speed falling-plate Duddell oscillograph, which was connected as a voltmeter between the brush and a trailing spring attached to the back of the brush, and separated from it by a sheet of mica $\frac{3}{64}$ in. thick. While both brush and spring were touching the same segment the oscillograph registered the fall of E.M.F. from carbon to segment, but as the carbon left the segment, the induced E.M.F. caused a current to flow through the instrument to the segment just left. As the spring traversed the mica between the segments the circuit was broken and the deflection fell to zero, but in many cases the brush bridged this, and the E.M.F. merely dropped to the first value. The use of a

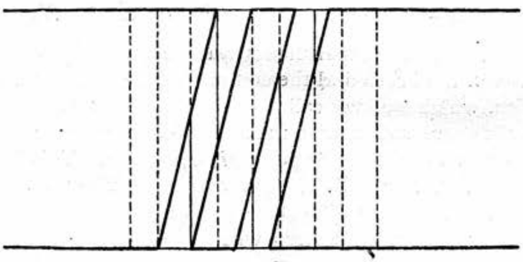

FIG. 7.

circuit in parallel with the break tends to reduce the E.M.F., but in most cases the resistance was some 160 ohms, so that a very fair idea of the sparking E.M.F. was obtained. The direction of the E.M.F. indicates whether the current is from brush to segment or the reverse, and indicates whether the machine is under-compensated or whether over-compensation has set up a circulating current in the reverse direction. In the following diagrams the direction above the zero line indicates an E.M.F. in the direction of the main current, or under-compensation.

As the speed which was used in some of the tests, 870 revolutions per minute, involves 2,500 commutations per second at the brush, the resolving powers of even an oscillograph were severely taxed, and the waves are unavoidably much crowded. Further resolution by increasing the speed of falling was prevented by the weakening of the photographic trace. But for the most part it was only the height of the wave that was required, and a large number of waves gave a better value of the average E.M.F. required. In order to make sure of the action of the apparatus a slower speed was adopted at first. Fig. 8

shows the action at a speed of 150 revolutions when the motor was running light. The waves are quite distinct, falling into groups of three, the number of coils in a slot. The E.M.F. rises as the slot travels to the approaching pole piece out of the field of the commutating pole. The zero values show the mica separators, after which there is a rapid rise to the E.M.F. between brush and segment, followed by another rise as the brush leaves the segment. There is much irregularity of detail, and it can scarcely be expected that the currents will repeat with exact regularity. There are six ripples on each wave for which more than one cause can be suggested, and it would be

Shown by the second wave being > 1st & 3rd than 2nd in each group

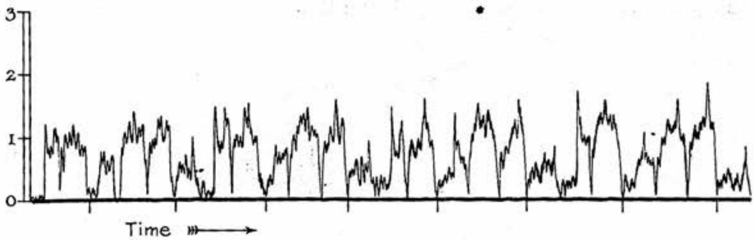

FIG. 8.—Running Light: Slow speed (150 revs.).

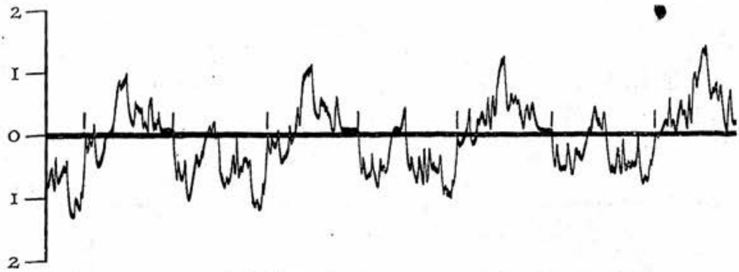

FIG. 9.—Running Light: 6 amperes round Commutator Poles.

unprofitable to follow them out in detail. The machine is under-compensated, and the sparking E.M.F. rises through the group of three coils as ~~the compensating pole becomes weaker~~. The maximum E.M.F. is only 1·7 volts, as the speed is very low, the E.M.F. between brush and segment being about 0·8 volts. The compensating poles were excited with more current, the motor still running light, and the curves showed a gradually increasing over-compensation. Fig. 9 was taken with 6 amperes, the armature current being 2 amperes, and much of the E.M.F. is now in the reverse direction. In fact, the waves group themselves in two sets of three, and in alternate sets the current is entirely in the reverse direction, the other parallel brush arm probably taking the driving current during this interval.

Containing the groups

× slot leaves the commutating pole

Repeating with different loads and the proper compensating current for each, the E.M.F. showed always under-compensation. This will be examined in more detail at a higher speed.

The motor was intended for a large range of speed, and we may therefore pass over the tests at normal speed, to examine its behaviour under the more trying conditions of a high speed and a weak main field. A speed of about 870 revolutions per minute was arranged, and Fig. 10 gives the light load values with an E.M.F. of 6 volts, Fig. 11 the full load values, in which the E.M.F. rises to 20 volts. The motor is considerably under-compensated, but nevertheless the brush dealt with this high E.M.F. with very little visible sparking, the mass of cold copper and the speed of separation doubtless contributing to this

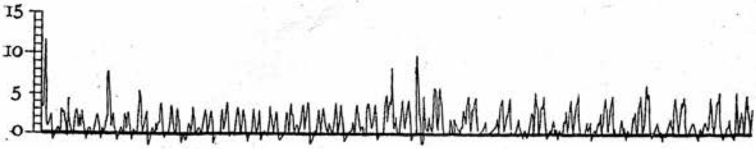

FIG. 10.

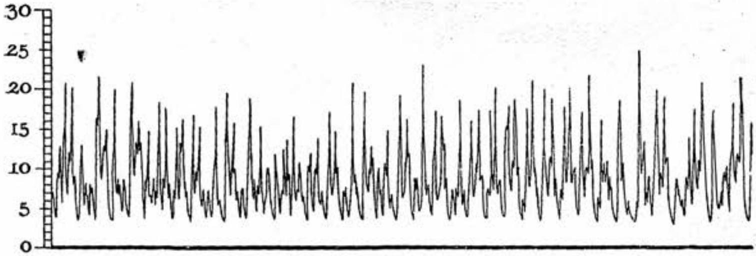

FIG. 11.

result. Fig. 12 shows the set of values obtained at these and at intermediate loads.

Further tests were made with no current round the compensating poles. The sparking was considerable, and even on half load the sparking E.M.F. rose to 32 volts. By shifting the brushes the current was taken up to full load with a sparking E.M.F. of about 32 volts. This is, of course, an abnormal condition, for the commutating poles were not removed, and their presence over the coil under the brush produces a strong magnetic field, due to the armature, which passes through the coil and naturally produces large circulating currents. The value of these will be examined later, and their magnitude easily explains this great E.M.F.

It had been in the mind of one of us that a brush with a trailing edge in the form of a very blunt V would act beneficially in reducing the current before the final break, and this seemed a suitable method for testing the device. The result, however, was not favourable, for the sparking E.M.F. was very little diminished. We have not followed up this method of testing different qualities and shapes of brushes, but it appears to be capable of much useful employment.

The foregoing experiments indicate that where the conditions assumed in the reactance formulæ are not fulfilled, it is important to determine whether the sparking E.M.F. will be large. At the same time they show that it need not be very small. In all cases of forced commutation, *i.e.*, where the current does not die down to zero by the action of a suitable E.M.F. in the short-circuited coil, but is merely throttled by the decreasing area of contact between segment and

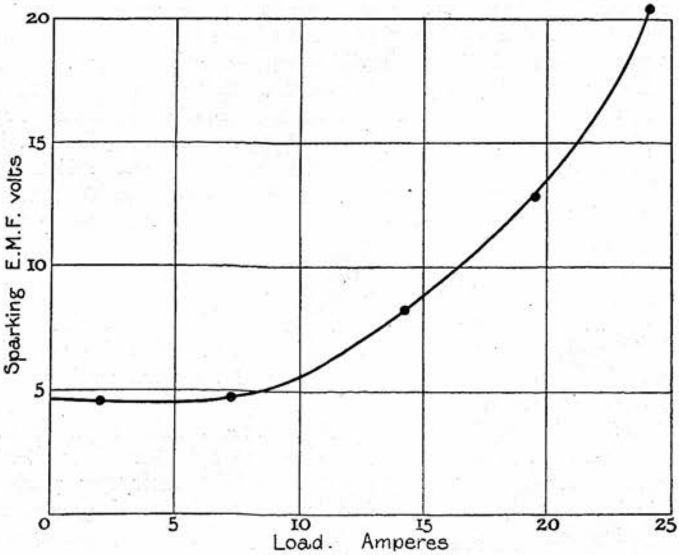

FIG. 12.

brush, often in spite of an E.M.F. in the coil tending to keep it up, in all such cases there will be an abrupt break and a possible spark. In many cases the main current will be unimportant, and the value to which the induced circulating current has risen will control the smoothness of the commutation. A broad brush will be a positive harm, as allowing the coil to come more into the field of the wrong pole, and giving time for the current to rise. The value of the current will be proportional to this field, to the speed of the machine, and to the number of turns in the coil, for the resistance of the coil itself will usually be small compared to the brush contact resistance. The E.M.F. produced by breaking this current $= L\, di/dt$, where L is proportional to the square of the number of turns (if they are all in the same slot), so that the sparking E.M.F. is proportional to the cube of the number of turns in the coil and the square of the speed. But the whole coil between two adjacent segments is not involved, if there are more than two sets of brushes, for the different sets break circuit successively, and the parts between the other brushes will readjust their currents without a spark. Hence the commutation is more easily forced in multipolar machines than in those with only two poles. To each of × test this, the sparking E.M.F. was determined with one brush on each of the four arms, and again with two brushes on two arms. In the first case the E.M.F. was 8 volts, in the second 15 volts, or nearly twice as great, the length of bar in which current is stopped being twice as long.

The same result is shown in the oscillograph curves of the current in the short-circuited coils shown by Mr. Catterson Smith (*Electrician*, April, 1906). Using several brushes, he found the current change its value by successive small steps instead of one large one, from which it may be concluded that there will be less tendency to spark.

The above estimation of the sparking E.M.F. assumes that the decrease of current, due to the diminishing area of the segment in contact with the brush, is sufficiently rapid to produce a sensible E.M.F. in the coil. But if this is not the case, and the self-induced E.M.F. does not appreciably influence the current, then the sparking E.M.F. will be proportional to the current at the moment of breaking, to the coefficient of self-induction, and to the speed or Lni, which is similar to the reactance voltage except that i has only a remote connection with the armature current, and depends on the resistance of the brush contact and the E.M.F. induced by the stray field. If it is possible to find a quality of carbon in which the resistance is fairly independent of current density the use of such brushes should sensibly decrease sparking.

For forced commutation it is preferable to have as small a magnetic field as possible in the interpolar space, to diminish the circulating currents. Hence a narrow air-gap and a large interpolar space are beneficial. Distortion of the field is then of little consequence, and weakening or even reversing the pole tip will not matter, so long as the field from the strengthened pole tip does not come down on the coil. The ideal machine with commutating poles does not experience forced commutation, but with incorrectly adjusted poles some forcing of the current is inevitable.

As a comparison with the foregoing curves, some tests were made on a simple motor without anti-sparking devices. The machine was a 6-pole, 55-h.p. motor made by Mavor and Coulson, running normally at 500 revolutions with 460 volts on the brushes. The pole shoes were square and the air-gap rather small for the size of the armature, being 3·9 mm. The slot breadth was 9 mm. and the breadth of the top of the tooth was 10 mm.

There were 282 turns with 142 commutator parts, or two turns per coil, wound in a two-circuit winding. There were six pairs of brushes, each of $1\frac{1}{8}$ sq. in. area. The nominal maximum current density was therefore 15 amperes per square inch.

As this machine was fitted with additional testing devices, which included a pair of spring contacts on the commutator, the contact resistance of the brush was eliminated by setting the two contact makers a short distance apart, the one just in front, the other behind the trailing edge of the brush. When they both touched the same segment the E.M.F. fell to zero, and the peaks of the curve read the E.M.F. in the coil as it left the brush and received the main current from the new side. The potential brushes were set at a distance little more than

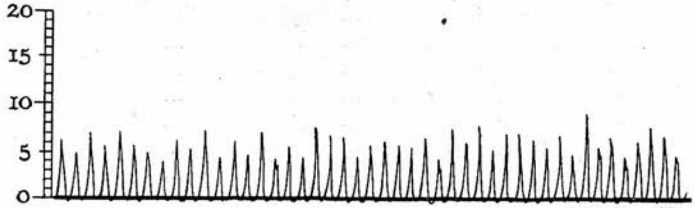

FIG. 13.

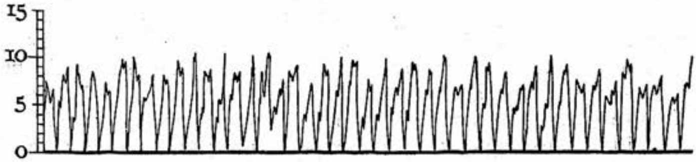

FIG. 14.

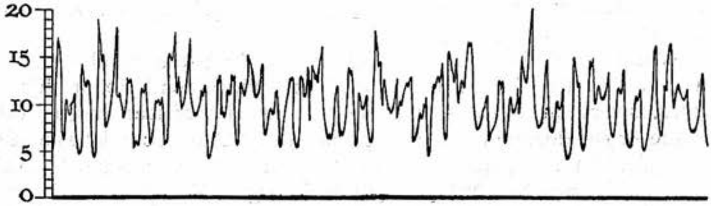

FIG. 15.

that of the breadth of the mica between the segments, so that the reading just included the spark and no more.

Setting the brushes in the most favourable position for running light, the curves gave an E.M.F. of 4 volts at this load, which rose to 6 volts at half load. It was found that if the potential leads were set with a very small gap, so that the trailing contact moved on to the mica after a contact lasting only $\frac{1}{32}$ in., the E.M.F. curve rose abruptly and dropped to zero (Fig. 13). On increasing the time of contact, the zero drop was only momentary, with a rapid rise as before, but there followed a momentary dip as the sparking E.M.F. ceased, and a further rise showed the E.M.F. induced in the coil by the stray field (Fig. 14), which was cut short by the contact coming on to the mica. The first rise in Fig. 14 is the same as the rise in Fig. 13, and that this is smaller than the E.M.F. induced by the stray field shows how thoroughly the current is controlled by the diminishing area of brush contact.

The following values of the first rise were obtained :—

		Armature Current.		Sparking E.M.F.
Brushes set for light load	...	7 amp.	...	3·5 volts.
" " "	...	23 "	...	3·5 "
" " "	...	46 "	...	4·0 "
" " 46 amp.	...	46 "	...	2·5 "
" " 46 "	...	7 "	...	2·0 "
" " 37 "	...	7 "	...	2·0 "
" " 37 "	...	37 "	...	3·0 "
" " 37 "	...	75 "	...	3·5 "
" " 75 "	...	75 "	...	2·5 "

The E.M.F. given here is the mean of somewhat irregular values, as there is no doubt that small changes of brush contact at the last moment will readily produce variations in the sparking E.M.F. For example, a mean reading of 3·5 volts will range from 3 to 4, or in places to 5. It must also be remembered that the supposed best position for the brush is a point difficult to ascertain, and the whole shift is very small, so that the minimum values are not consistent.

Additional readings were taken by the previous method from brush to contact, and the curves show the value of the contact resistance of the brush (Fig. 15). The brush contact is about 2·5 volts, and the first rise is about 2·5 to 3 volts, with a current of 48 amperes. The two methods, therefore, give similar results.

Without claiming any great exactness for these numbers, it is evident that the E.M.F. of self-induction, which tends to produce a spark, is very small in this machine, and variation of load and position of the brush does not create large changes. The machine has a very weak field in the space between the poles, for the air-gap is small and the distance between pole pieces is large. The number of turns per coil is small, the complete coil is divided into three parts by the brushes, and the speed is not high. There are therefore all the conditions for a very moderate sparking E.M.F. or good forced commutation, although the value of the reactance voltage is not especially low, being $3\frac{1}{4}$ volts. A further examination into the process of commutation of this machine will be considered below.

VIII.—Distribution of the Magnetic Field, and Influence of Circulating Currents in a Motor with Commutating Poles.

Readings of the magnetic field of the machine were taken by means of a search coil on the armature, connected through slip-rings to the oscillograph. Fig. 16 shows the field due to the main poles, and Fig. 17 represents the influence of the commutating poles, with the

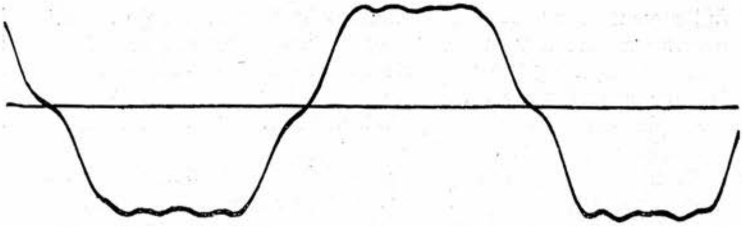

FIG. 16.—Armature driven externally. Brushes lifted. No current round Commutator Poles.

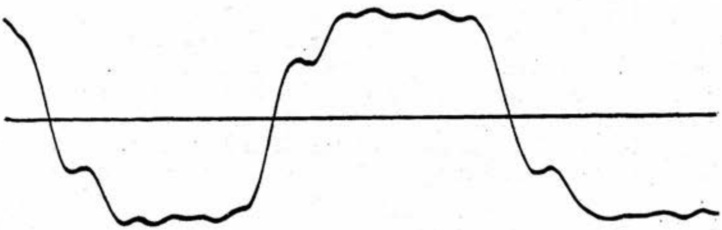

FIG. 17.—Armature driven externally. Current round Commutator Poles 28 amperes (full load current). Brushes lifted.

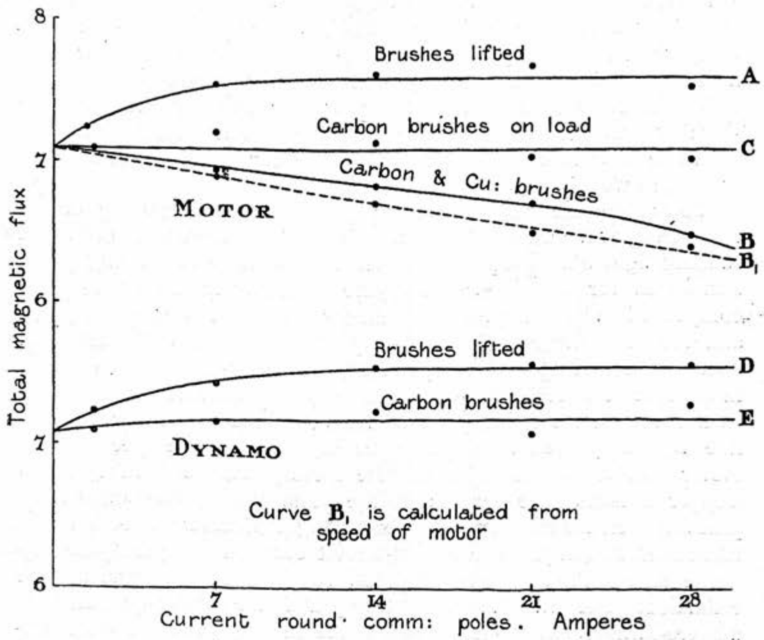

FIG. 18.

full current round the coils. Exciting these as for a motor, a series of curves was taken with increasing currents, and the resulting total areas, representing the magnetic flux, are shown in curve A (Fig. 18). It is clear that by half load the commutating poles are saturated, and the rapid rise of the sparking E.M.F. in Fig. 12 has already indicated that this was probable.

It has been shown by Messrs. Walls and Smith (*Electrician*, April 6, 1906) that in a stationary armature the magnetic flux of the commutating poles is independent of that due to the main poles, and it may be regarded as crossing the latter at right angles. These curves indicate that this is the case, for the effect is merely a hump on one side, the main portion being unaffected. The brushes were put down in the central position, and similar curves taken at different loads, the load current exciting the commutating poles. The brushes being central, there is no demagnetising action exerted directly by the armature current. The commutating poles are demagnetised by the magneto-motive force of the armature. There are powerful currents in the short-circuited coils, which produce violent fluctuations of magnetic field under the commutating poles, and which would tend to magnetise the main field. But the areas of the curves, which are plotted in line C, are almost constant, showing that the increased reluctance of the main circuit due to the distortion of the field has counterbalanced the increased M.M.F. Figs. 19, 20, 21 are examples of the curves obtained at light load, half, and full load respectively. The circulating currents steadily increase with the increase of load, as the reversed field under the commutating poles increases.

The same tests were carried out with copper brushes, but the sparking prevented the trial of heavy loads. The results were much the same as with carbon brushes, but the circulating currents were greater, as would be expected.

To examine the influence and magnitude of the circulating current apart from armature distortion, a series was taken with the armature running light and a separate current round the commutating poles, excited as for a motor. This gave a gradually increasing over-compensation. Figs. 22, 23 give the results with 14 and 28 amperes, and the magnetic flux for each is plotted in curve B, Fig. 18. The commutation being over-compensated, the short-circuit currents are in the reverse direction, and the total field is considerably diminished. As a check on the figures derived from the areas of the curves, the line B_1 was plotted from values calculated from the speed of the motor, and it will be seen that the correspondence is fairly close. Copper brushes gave very much the same results, the points lying practically on the same line B. Examining the curves in detail, it will be noticed that in places the short-circuit currents completely demagnetise parts of the commutating poles, from which their value may be estimated. The M.M.F. across the gap at full load is 1,700, and the ampere-turns 1,350. There are for the most part two coils short-circuited under the brush, containing 24 turns, so that the current must amount to some 60 amperes, and its maximum value is probably much more in one of the coils. Their influence on the main field was determined by measuring the area, and the demagnetising effect was found to be some 10 per cent. Calculating from the characteristic curve, this represents 350 ampere-turns, the average value given by this

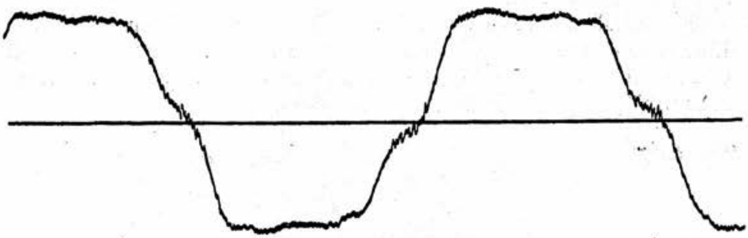

FIG. 19.—Field on Load. Running light : 2 amperes.

FIG. 20.—Half Load.

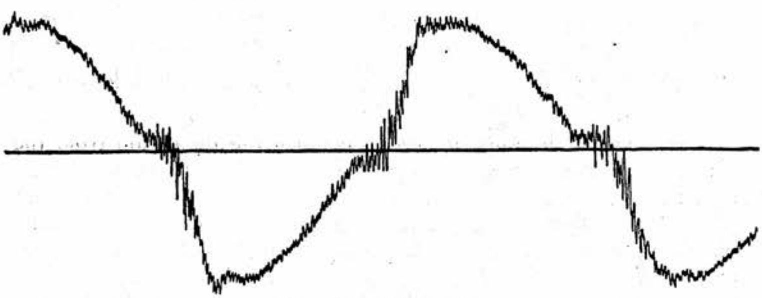

FIG. 21.—Full Load.

method being much less than the maximum value given above. No doubt such large currents, several times the normal current, are not to be anticipated in a well-designed machine, but it is clear that there are great possibilities if the design is incorrect. The sparking E.M.F. obtained under the same conditions was found to be very large.

An attempt was made to use copper brushes, but the sparking and disturbance of the field were so violent that the motor began to hunt, and readings were impossible above a magnetising current of 7 amperes.

Another series was taken with the commutating poles excited as for a dynamo, *i.e.*, in the wrong direction. With the brushes lifted, so that no disturbance could take place, the values of line A were obtained again, as shown in D.

The brushes were then put down and the machine run as a motor. Line E gives the results, corresponding to line B. The short-circuit currents magnetise the main field, and the total flux rises as the current round the poles increases.

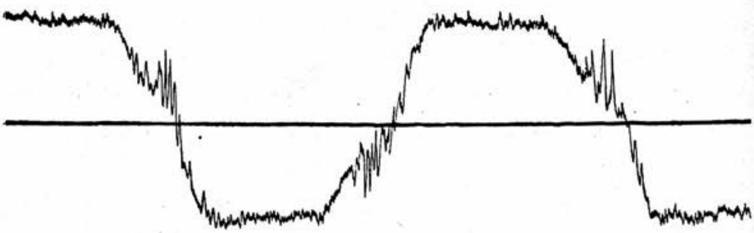

FIG. 22.—Current round Commutator Poles 14 amperes : Brushes down.

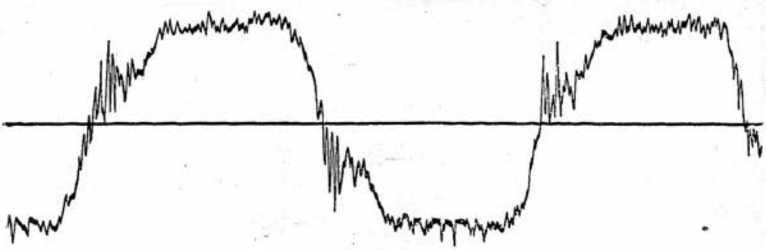

FIG. 23.—Current round Commutator Poles 28 amperes : Brushes down.

These curves in Figs. 19, 20, 21, confirm the deduction from the curves of sparking E.M.F., that the commutating poles are not sufficiently powerful, and they further show the great risk of such poles when incorrectly designed, for the reluctance of the magnetic circuit, in the air-gap of which the short-circuited coils lie, is small, and a small want of balance of magneto-motive forces will produce a considerable magnetic field. By using such poles the maker expects to be able to allow a large number of turns in the armature coil, and the liability of sparking is increased, in addition to the disadvantage of the heating effect of the short-circuit currents on armature commutator and brushes, and the loss of power. In the simple machine there is much less danger of unsatisfactory commutation.

It is only fair to the makers of the motor to state that this particular machine was one of the first they had made, and it should be added that, notwithstanding the errors revealed in these tests, the motor runs with little sparking even at high speeds.

The risk of using too broad a brush is also clearly brought out. These should be as narrow as possible, in order to curtail the time during which extra currents can be produced. Whether under or over compensated, the motor will tend to spark if the brush is broader than is absolutely necessary, and as we have seen in the first part of the paper, a high current density makes little difference to the commutator losses.

In Mr. Creedy's paper (*Journ. Inst. El. Eng.*, April, 1905), among experiments on an alternate-current series motor, is one on a direct-current series motor, in which he measures by a falling-plate oscillograph the fluctuations in the magnetic field and the armature current, finding ripples in the magnetic field and the current. He attributes this, in part at least, to variations of brush resistance, and with a series motor such an explanation is possible ; but it was much more probably the same action that has been noted above. Mr. Punga, in the discussion of the paper, suggests that short-circuit currents may be the explanation. It may be here remarked that Mr. Punga treats the resistance of a brush as constant, and the E.M.F. between brush and segment as proportional to the current density, which vitiates some of his formulæ.

The concluding portion of the paper will be read at the meeting, the MS. not being completed in time for printing.

Institution of Electrical Engineers.

GLASGOW LOCAL SECTION.

CONTINUATION OF PROF. F. G. BAILY'S AND MR. CLEGHORNE'S PAPER,

SOME PHENOMENA OF COMMUTATION.

IX.—MEASUREMENT OF CURRENT IN THE SEGMENT UNDER THE BRUSH.

The foregoing experiments gave only indirect information concerning the current flowing into the brush from a segment, and so far as we know, no direct measurements of the rise and fall of the current in a segment have been made. As the current in a segment endures for an extremely short space of time, either an oscillograph or a contact-maker must be used. The resistance of the lug itself is too small to permit of a reading of the fall of potential, but a resistance inserted for the purpose would tend to divert the current into adjacent lugs also in contact with the brush. Accordingly three consecutive segments were provided with a resistance of 0·018 ohms, and readings were taken from the central one. The current is then unaffected, except that the total armature resistance is momentarily increased by some 5 per cent., which will not sensibly influence the result. Currents in the short-circuited coils will be reduced, but the dimensions of these will vary so much between one machine and another, and with the width of the brushes, that their exact value in the particular motor examined is not of great importance. The resistance was arranged primarily for use with an oscillograph, which method was abandoned, and it was unnecessarily large for the method finally adopted.

The contact-maker method consisted in charging a condenser with an E.M.F. at a particular instant by means of a pin and spring. On the terminals of the condenser was a galvanometer, which with a very small consumption of the charge gave the E.M.F. The loss of charge was only 6 per cent., or the average E.M.F. 3 per cent. below the value to be measured. The readings were standardised in two ways: (1) by placing a standard cell directly in the galvanometer circuit; (2) by placing the cell in the contact-maker circuit in lieu of the potential to be measured. The two readings agreed to 0·2 per cent., showing that no errors crept in at the slip-rings. For measuring the current in the lug, potential leads were taken off to a slide-ring and to a contact pin, and from these to the condenser. The E.M.F. between brush and segment was read in the same way, the pin being fixed in the

 Cor E.M.F. measuring Apparatus

segment, and a change-over switch brought either into action. The positions of the contacts were adjusted to give readings at nine points, dividing the distance through which the segment was in contact with the brush into eight equal parts. The whole circuit was carefully tested for leakage and found to be perfectly sound.

The machine examined was the 55 H.P. motor previously used. Although this has six poles and three brush arms in parallel, it was thought desirable to avoid complications, and only one brush arm was employed. Otherwise nine lug resistances would have been needed, and three simultaneous readings of current by three complete sets of apparatus. Though much interest would attach to the determination of the respective currents in the three parallel circuits, this part must be left to the future.

The use of a single brush arm made advisable a restriction of the current to half load, although with the brush in the most favourable position a greater load could have been carried. The brush area was 2 ins. axially and nominally $\frac{3}{8}$ in. circumferentially, which was reduced actually to $\frac{5}{16}$ in. The brush width was barely more than the width of a segment and mica strip, so that not more than two segments were active together. The brush pressure was 40 oz. per square inch, the high pressure rendering steady readings more probable. The full exciting current was used, and a pressure of 460 volts gave a speed of 480 revolutions per minute, which was maintained all through. The brush examined was the negative, current passing from segment to brush.

Readings were taken with the brushes central, set back, and set forward, with currents of 7, 25, and 45 amperes at each position. Repetitions of readings showed some changes in the form of the curve, which would be to some extent influenced by changes in the brush contact, and as each set of readings occupied about an hour, it is probable that such changes occurred even during a single set. The most consistent examples are shown in Figs. 24, 25, and 26. [In Fig. 24 the current is 35 amperes, not 25.] It will be noticed that the current does not start until after the first division, due to the leading edge of the brush being slightly bevelled, as was found afterwards. The upper curves show the three currents, the lower curves the corresponding E.M.F.s between brush and segment, and the central diagram gives as ordinates the contact area between brush and segment at each point. For a short space in the middle the whole segment is in contact with the brush, reducing to zero on either side, where the current begins or ceases.

The first rise of the current is extremely rapid, amounting in the curve 45 in Fig. 24 to a rate of increase of 200,000 amperes per second. If this is multiplied by the inductance of the coil in which this change takes place, the result is an E.M.F. of 5 volts, the counter E.M.F. in the short-circuited coil. Referring to the E.M.F. curve, it has a value in the coil just before contact of 7 volts. This is the E.M.F. due to the leakage field. The E.M.F. drops promptly to about 1 or $1\frac{1}{2}$ volts, the rest of it being used to overcome the counter E.M.F. in the coil, so that the slope of the current curve is closely in accordance with this E.M.F. In Fig. 25 the E.M.F. and rate of increase of current are almost as great, but in Fig. 26 the E.M.F. is very small, and the rate of rise of the current is much slower. But this E.M.F. is not the only cause of the

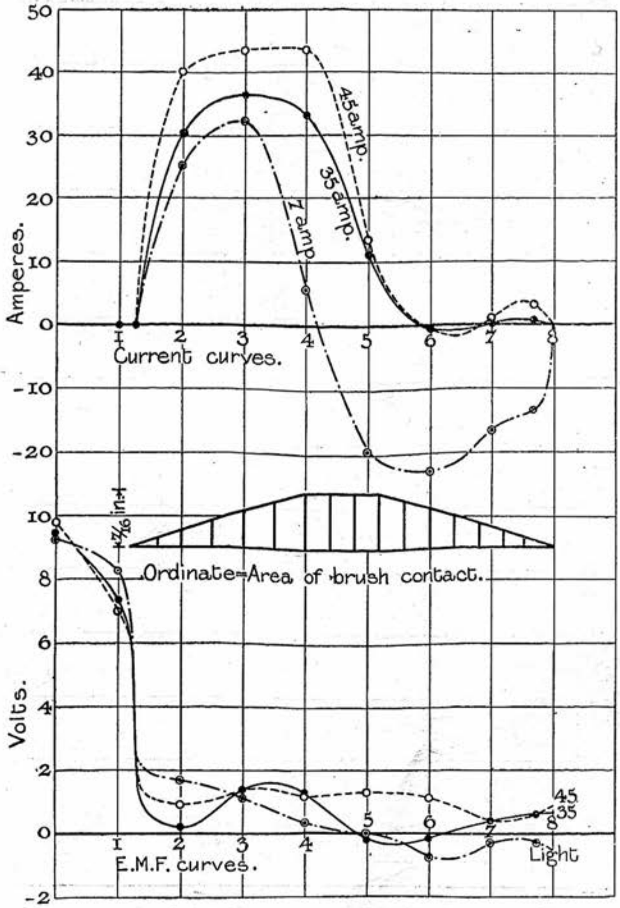

FIG. 24.—Current and E.M.F. in Segment, Brush behind Centre.

current entering the new segment, for in that case the rate of rise would be the same for all currents. The resistance of brush contact in the previous segment forces the current into the new one with an E.M.F. which increases with the current, and hence the rate of rise is greater, the larger the current. In Fig. 24 this effect is small, but in Fig. 26 it is the principal factor, and the rate of rise differs markedly for the three currents.

Examining the next parts, it is notable that the current has not only reached its maximum before the full contact, but has even begun to fall either before or soon after full contact is attained. On light load

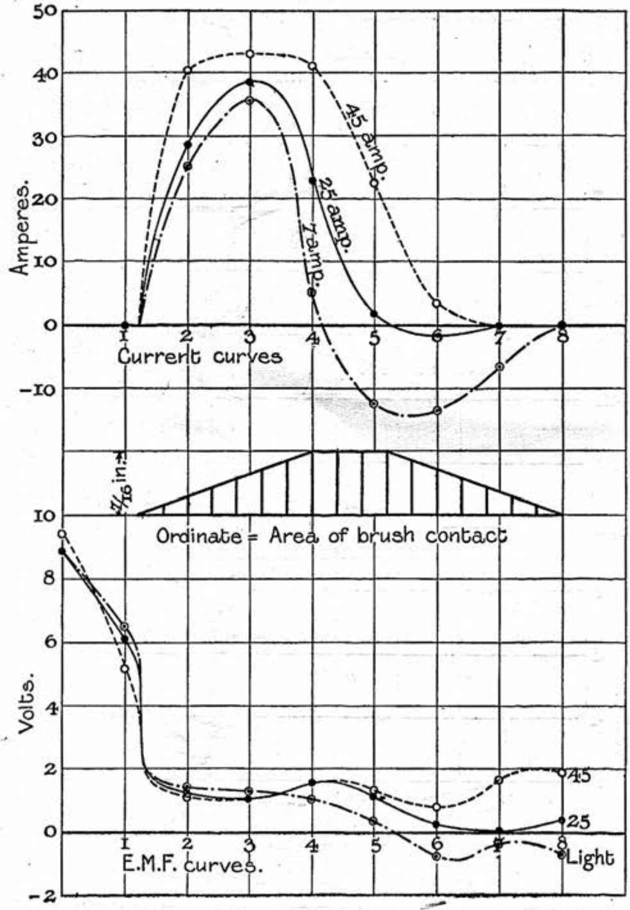

FIG. 25.—Current and E.M.F. in Segment, Brush in Neutral Position.

there is an excess of reversing E.M.F., which causes a reverse or circulating current, large in 24 and small in 26. In the former it is dying away slowly, as the coil moves out of the field, when the diminishing brush area cuts it off abruptly, with a corresponding rise in the E.M.F. curve. With 35 and 45 amperes the current does not rise

in Figs: 24 and 25

again to any appreciable extent, and commutation is evidently perfect. Owing to the distortion of the field by the larger currents, there is a slight reversal of the field, causing the current to start in the wrong direction, until cut off by the brush resistance. The phenomena in Fig. 25 are very similar on a reduced scale. In fact, up to half load

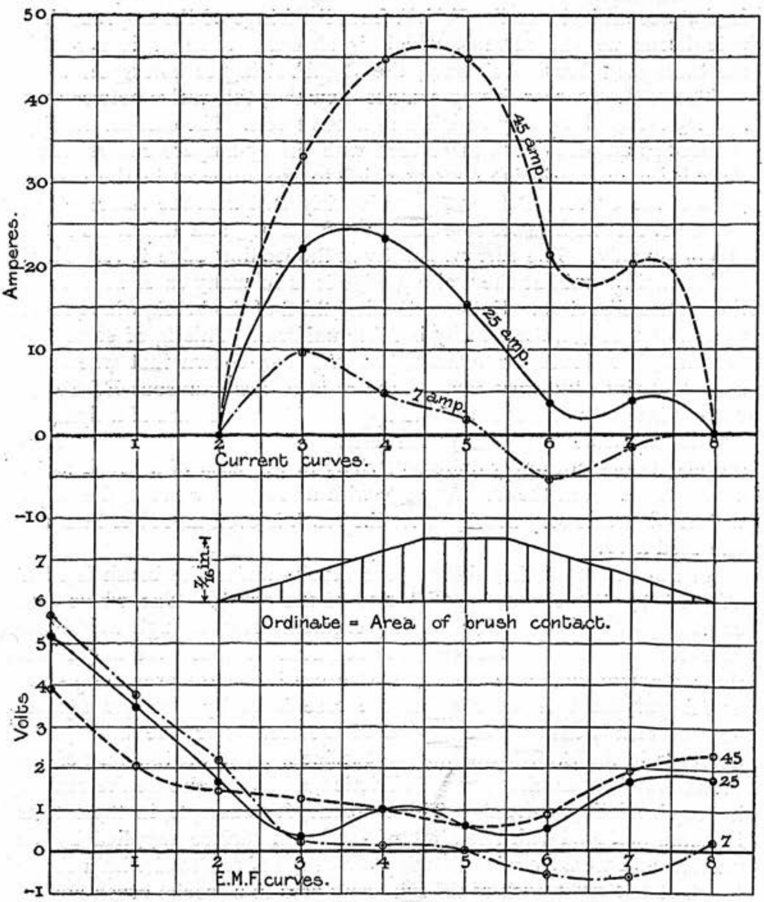

FIG. 26.—Current and E.M.F. in Segment, Brush in front of Centre.

this central position of the brushes is better than the previous one. Probably an intermediate point between 7 and 8 would show the half-load current rising again, as indicated by the E.M.F.

Fig. 26 shows the effect of insufficient reversing E.M.F. at first, which does not matter, and of the wrong E.M.F. at the end, which is more important. Without this E.M.F. the current of even 45 amperes would evidently have risen and died down by the action of the brush resistance alone, finishing easily by the end of the contact. It may be of interest to say that, taking t as the half-time of contact, and R as the resistance of coil, lug, resistance, and brush contact (at the full), the product Rt is twice the inductance of the coil, a condition which on some theories of commutation should insure satisfactory results. In the present instance the E.M.F. from the fringe of the approaching pole keeps up the current, which is abruptly brought to zero by the increasing brush resistance, the E.M.F. rising to correspond.

The E.M.F. curves during contact show that this varies between 0·5 and 1·5 volts, which may be taken as about 1 volt. The current density is about 90 amperes per square inch with the 45-ampere curves when there is full or nearly full contact, rising to 150 amperes in the earlier parts of the curve. This corresponds fairly well with the values given in Part I., for the brushes resembled the S quality, and this value is for one brush only. The current density at the leading edge is very high, falling rapidly until at the trailing edge it is in many cases zero or in the reverse direction. But over the first third of the brush, where most of it gets through, the density is fairly uniform. This is of some importance, for Professor Arnold (*loc. cit.*) has shown that when the current varies with great rapidity the ratio of instantaneous E.M.F. to current is nearly constant, and he applies this to the case of a dynamo brush. Whatever the value of the resistance may be under these conditions, it does not apply quite so strictly to the case of a brush as he assumes. Even at the trailing edge with a reversed current, the value will not fluctuate very much, unless the brush is even narrower than the one used here.

It will be noted that the current density under the brush is little affected by the circumferential size of the brush. The whole line current passes through the leading segment, even though the larger portion of the brush is touching the segment behind. We may recall the statement made in Part I., that excessive brush area serves no useful purpose, and we see that the case is really stronger against low current density than appeared before. For the anticipated decrease in the E.M.F. will not be obtained, while the idle part of the brush is at best wasting power in friction, and may also be the seat of heavy circulating currents. This machine, for example, in these tests is taking half load with one-ninth of the brush surface supplied by the makers, and we have taken it up to two-thirds of full load with a single brush of one-eighteenth of the full brush area in a special brush holder, with no sparking and with a pressure of 30 oz. per square inch. The current density must have been very great, and possibly this extreme reduction of brush area was not economical, but it is instanced to show that high current density alone will not cause sparking. In fact, it will tend to increase the brush resistance effect in forced commutation at the trailing edge, and to lower the sparking E.M.F. The only risk lies in overheating, if sparking should occur, for it will be concentrated over a shorter line with less cooling surface.

The curves of current were obtained with very steady readings, though successive tests showed some irregularity of outline. But in spite of probable changes during a single set of readings, the mean value of a succession of waves gives a height closely equal to the line current. The curves of E.M.F. were not so reliable, and it is extremely probable that the contact resistance at any one point under the brush will fluctuate, causing a corresponding fluctuation in the E.M.F. There are scarcely enough points for accurate plotting of the bends, but an increase in their number would have protracted the duration of an experiment, and would have increased the probability of change of conditions. There is a certain uniformity in the undulations which tends to show they are not simple irregularities, but an analysis of the current density and E.M.F. at each point would not be safe.

While the results of these last tests do not bring out any new phenomenon which has not been, or could not be, conjectured beforehand, they emphasise the fact that the leading edge of the brush is really the important part from the current-carrying point of view, and that the trailing edge should be reduced to its narrowest limits. The leading half should be of the best and most heavily graphitised carbon, and possibly the metallic impregnations sometimes used would be still better. But the trailing half should have a much higher resistance, preferably obeying Ohm's law as nearly as possible. The old carbon-fronted gauze brushes carry out this idea, but a single composite brush of uniform wearing qualities throughout will be more easily applied, and will require less attention. There is no need for several laminations, for these circulating currents cannot get through the leading part of the brush, and low resistance laminations at the trailing half will be harmful. The high resistance at the trailing edge will force the current to the new segment in front, which is all that is required.

The second point to which attention may be drawn is that the brush has far more power to commutate the current than is usually believed, at least by writers on dynamos. A low inductance is necessary, but a uniform high contact resistance is not advantageous, for while it hastens the fall of current in the trailing segment it also checks the rise in the new one. A reversing E.M.F. is desirable, but not necessary, as is shown by Fig. 26, where commutation takes place without its aid, x or rather with it in the wrong direction and it must be noted that, while the machine is only on half load, yet it is working with only one brush arm, and all three coils are commutated at once. The conclusions drawn from the curves of sparking E.M.F. are therefore substantiated, that the less stray field there is the more safely the machine will commutate. So long as the armature field is kept away from the short-circuited coil, the strength of the main field may be reduced to any limits. If the armature coils have reasonably small inductance, then a wide interpolar space, a narrow air-gap, good brush holders and brushes not too broad, will hardly fail to produce sparkless commutation and a cool commutator.

In conclusion, we wish to express our thanks to Mr. W. G. Griffith and to Mr. H. J. Ireland for their assistance in the work on the resistance of brushes, and to acknowledge our gratitude to the Carnegie Trust for a grant in aid of this research. Their bestowal of a research scholarship has given leisure to one of us for the somewhat laborious experimental work which has been entailed, and the machines used in the tests form part of the new equipment of the electrical engineering laboratory in the Heriot-Watt College, to the purchase price of which they largely subscribed.

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